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14. ABSTRACT

This report provides findings from the research conducted under the Phase - 1 of RT-18-Valuing Flexibility. The primary goal of this research project is to identify, develop and validate sound quantitative methods, processes, and tools that will enable DoD leadership and program managers to make a convincing case for investments in system flexibility when acquisition decisions are made. The research during this period focused on identifying current quantitative MPTs for valuing flexibility in DoD context, and delivering an initial capability to value investments that provide the flexibility to handle foreseeable sources of change, using easy-to-understand monetizable terms, such as the effect of the investments on total cost of ownership or return on investment. We conducted a critical evaluation of the theoretical foundations underlying current approaches, the dimensions of flexibility measures of flexibility, value functions, and methods for incorporating flexibility - both at the design phase and the operational phase, to identify strengths and weaknesses of each approach. During this period, we also explored the development of an analytical framework based on sound mathematical constructs. This report also presents our advances in defining and formalizing the value of flexibility and the underlying capability-need-value architecture that can be used by systems acquisition decision-makers.

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ABSTRACT

This report provides findings from the research conducted under RT-18: Valuing Flexibility project during the first seven month period. The primary goal of this research project is to identify, develop and validate sound quantitative methods, processes, and tools that will enable DoD leadership and program managers to make a convincing case for investments in system flexibility when acquisition decisions are made.

The research during this period focused on identifying current quantitative MPTs for valuing flexibility in DoD context, and delivering an initial capability to value investments that provide the flexibility to handle foreseeable sources of change, using easy-to-understand monetizable terms, such as the effect of the investments on total cost of ownership or return on investment. We conducted a critical evaluation of the theoretical foundations underlying current approaches, the dimensions of flexibility, measures of flexibility, value functions, and methods for incorporating flexibility – both at the design phase and the operational phase, to identify strengths and weaknesses of each approach. During this period, we also explored the development of an analytical framework based on sound mathematical constructs.

A review of the current state-of-the-art showed that there is little unifying theory or guidance on best approaches to measure flexibility, quantify value of flexibility in a prospective systems acquisition or which MPTs work best in which situations. In fact, the analytical basis for defining and valuing flexibility is missing. Considering this major gap in the current state-of-the-art the primary focus of our research activities is in developing a coherent value based definition of flexibility that is based on an analytical framework that is mathematically consistent, domain independent and applicable under varying information levels. This report presents our advances in defining and formalizing the value of flexibility and the underlying capability-need-value architecture that could form the basis for developing tools that can be used by systems acquisition decision-makers to conduct tradeoff analysis between flexibility and other system performance measures of interest.

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1 PROJECT OVERVIEW AND GOALS

The primary goal of this research project is to identify, develop and validate sound quantitative methods, processes, and tools that will enable DoD leadership and program managers to make a convincing case for investments in system flexibility when acquisition decisions are made. This research will enable systems engineers to determine "the value of flexibility" in various situations, and thus enable DoD acquisition personnel to make more informed decisions on "how much to invest in flexibility". A further goal is to identify gaps between current capabilities and DoD needs for both valuing and improving the flexibility of military systems, and to create a roadmap for researching and developing such capabilities.

This report provides details of the tasks completed under this project during the first phase.

1.1 Motivation and Need

Flexibility is almost universally perceived as a good thing. Systems acquisition in the DoD is no exception, where programs typically strive to infuse some degree of flexibility into the system being developed. It is becoming increasingly clear that future DoD systems need to be highly adaptive to rapid changes in adversary threats, emerging technology, and mission priorities, both during development and during operations.

Traditionally, however, complex DoD systems have been designed to deliver optimal performance within a narrow set of initial requirements and operating conditions at the time of design. This usually results in the delivery of point-solution systems that fail to meet emergent requirements throughout their lifecycles, that cannot easily adapt to new threats, that too rapidly become technologically obsolete, or that cannot provide quick responses to changes in mission and operating conditions. It is possible to design engineering systems with degrees of freedom such that they exhibit flexibility and/or robustness in future operating environments. However a critical challenge is to assess how much such an upfront investment in design with various degrees of freedom (margins, generics, service-oriented interfaces, product-line architectures) is worth to decision-makers, and how this added flexibility impacts the various performance attributes of the system.

To answer these types of questions, we must develop valid methods to measure the value of flexibility. First, we need to know how much flexibility we have in a given system, so that we can compare the design flexibility across systems, as well as the flexibility of different design options within a given system. Despite its wide usage and high regard, there is little consensus on even a formal definition of flexibility. Making

this task more challenging is the fact that there are a litany of "–ilities" that appear to be closely related to the notion of flexibility, including *adaptability, robustness*, *agility*, *changeability*, *modularity*, *interoperability*, *modifiability, scalability*, and *versatility*.

With a better sense of what is meant by flexibility, we can then explore the notion of its value. There is a plethora of questions to consider. Is flexibility always a good thing or are there circumstances where its value is diminished? And how precisely can we measure that value? What is known regarding the correlation—either positive or negative—between the flexibility of a system and its cost, schedule, and performance? How much does flexibility really cost, both in terms of money and other system tradeoffs? Can a flexible system save us money, and if so, does this apply to all phases of the system lifecycle or only to the procurement phase or the operations and maintenance phase? Similarly, can flexibility provide a reduction in lifecycle cost by extending the life of a system? Does it allow us to field a system more rapidly or respond to new threats more quickly and/or effectively? Do we know if optimal performance goals are diametric to flexibility goals?

Finally, once we know what flexibility is, what its value is, and how we measure it, we can then focus on how to achieve it. The key questions are: How do we structure a program such that it fosters designflexibility? Are there specific design principles that can be used to instill flexibility into the system design? Moreover, if certain methods do contribute to flexibility, can this relationship be proved formally? Is there a relationship between flexibility and other key macro-elements of the system, such as architecture and acquisition strategy? Do we need to modify acquisition practices and procurement processes to enable the implementation of flexibility?

As our review of the current state-of-the-art will show, there is little unifying theory or guidance on best approaches to measure flexibility, quantify value of flexibility in a prospective systems acquisition or which MPTs work best in which situations.

Considering this major gap in the current state-of-the-art the primary focus of our research activities is in developing a coherent value based definition of flexibility that is based on an analytical framework that is mathematically consistent, domain independent and applicable under varying information levels.

1.2 Scope and Specific Project Objectives

The primary aspect of valuing flexibility emphasized by the sponsors is to focus on flexibility to deal with foreseeable sources of change, to demonstrate the value of flexibility in quantitative, monetizable terms familiar to DoD organizations such as Cost Analysis and Program Evaluation (CAPE), and to identify mathematical tools for determining the monetized value of flexibility. Some further focus areas in which the sponsors have expressed interest involve ways to improve flexibility via quantifying departures from requirements as the sources of change, via determining enablers for

providing modular margins to improve flexibility, and via determining decision drivers for product line scope decisions.

The Phase 1 of this project is being performed over two periods. The first 7-month period, the subject of this report, focused on identifying current quantitative MPTs for valuing flexibility in DoD context, and delivering an initial capability to value investments that provide the flexibility to handle foreseeable sources of change, using easy-to-understand monetizable terms, such as the effect of the investments on total cost of ownership or return on investment. We conducted a critical evaluation of the theoretical foundations underlying current approaches, the dimensions of flexibility, measures of flexibility, value functions, and methods for incorporating flexibility – both at the design phase and the operational phase, to identify strengths and weaknesses of each approach. During this period, we also explored the development of an analytical framework based on sound mathematical constructs that will be refined in the second period.

The second 6-month period will focus on completing the development and comparative evaluation of more advanced methods of valuing flexibility. These analyses will compare the various methods across representative DoD change adaptation situations using a variety of case studies of completed and prospective projects. This will enable DoD projects to determine which valuation methods to use in which situations. These results will also identify significant gaps between available capabilities and DoD needs, both for valuing and fielding flexibility. The gap analysis results will then be used to develop a research roadmap for developing the needed capabilities by mapping current capabilities on future DoD operational requirements.

2 Critical Review of the State-of-the-Art in Valuing Flexibility

In general, the terminology used in literature related to flexibility is a quagmire. In most articles on the subject of flexibility, the definition is not explicitly provided, thus leaving the reader to infer or guess at its meaning. In many cases, the problem extends to—and is exacerbated by—the careless usage of many of the other non-traditional system design parameters (i.e., the so-called "–ilities"). For instance, the terms "flexibility" and "adaptability" are often used interchangeably, or conflated with descriptors like *agility*, *modifiability*, *changeability*, *universality*, *scalability*, etc.

We begin by considering how flexibility is used across disciplines, and then narrow our attention to the domain of particular interest to us: Designing a flexible defense system or product. Once we have carefully examined the various definitions of flexibility, we will immediately consider its linguistic doppelganger: Adaptability. An integrated examination of these two terms should help clarify both. In turn, this will help contextualize the role of related concepts such as *agility*, *modularity*, *interoperability*, and *robustness*, which we will also briefly examine and synthesize. Our goal is to formulate a precise definition of flexibility that can provide the foundation of subsequent discussion regarding flexibility, and will lend itself to quantifying its value, and ultimately help us implement it.

2.1 Definitions and Quantitative Measures of Flexibility

While there is no clear agreement on the definition of flexibility, there is, at least, broad acknowledgment of this fact. The lack of an unambiguous, consistent definition for flexibility is lamented by numerous authors (e.g., [Saleh, 2001; Saleh, 2003; Nachtwey, 2009; Fitzgerald, 2009; Bordoloi, 1999]). And of the "–ilities," there is reason to believe that "flexibility" is the most exploited. In one study, the authors presented evidence showing that the term "flexibility" (and its variants) is used in a colloquial sense much more often than other design terms like "robustness" and "optimize" (and their variants), concluding that the concept of flexibility lacks "scholarly maturity"[Saleh, 2009]. However, this author also supports the notion that the "concept of flexibility is today where the concept of quality was some 20 years ago," suggesting that its definition and quantification are destined to mature [Saleh, 2009].

Following is a small sampling of the types of definitional deviation that can be found in the literature on flexibility. Flexibility is—

- "The ability to change or react with little penalty in time, effort, cost or performance" [Upton, 1994]
- “The property of a system that is capable of undergoing specified classes of changes with relative ease” [Suh, 2007]
- “The best possible performance in the face of environmental variability”[de Groote, 1994]
- “Adaptable and capable of change” [Gustavsson, 1995]
- “There is a consensus in the literature that flexibility, sometimes called `versatility’, means adaptability to changes” [Barad, 1997]

Many of the definitions found in literature are too broad and self-referential to be of use in quantitative assessments and decision making. Also, the tendency to use “adaptability” as a means of explaining “flexibility” occurs frequently, and serves to obfuscate the matter further.

Several researchers have attempted to define specific types of flexibility. Below is a list of some of these non domain-specific flexibility subtypes, along with one sample definition from the literature.

- Organizational Flexibility: “The ease with which the organization's structures and processes can be changed” [Nelson, 1997]
- Process Flexibility: “The ability of people to make changes to the technology using management processes that support business process changes” [Nelson, 1997]
- Structural Flexibility: “The capability of the design and organization of a business process changes” [Nelson, 1997]
- Technology Flexibility: “The ability to adapt to both incremental and revolutionary change in the business or business process with minimal penalty to current time, effort, cost, or performance.” [Nelson, 1997]
- Management Flexibility: “The ability of management to affect the course of a project by acting in response to the resolution of market uncertainty over time” [Saleh, 2003]
- Product Flexibility: ““Product flexibility can be defined as the degree of responsiveness (or adaptability) for any future change in a product design” {{180 Rajan,Palani,P.K. 2003}}.
- Decision Flexibility: “The number of remaining alternatives after a first commitment is made” [Saleh, 2009]
- Operational Flexibility: “Attributes of the system that emerge in the face of unanticipated changes” [Nilchiani, 2006]
- Development Flexibility: “Can be expressed as a function of the incremental economic cost of modifying a product as a response to changes that are external (e.g., a change in customer needs) or internal (e.g., discovering a better technical solution) to the development process” [Thomke, 1998]

- Design Flexibility: "Implies that the system has been designed with certain characteristics" which "may not be necessary or justified in the context of optimising the system for the immediate mission (or set of requirements) … However, these characteristics will allow the system to be easily modified should these requirements change after it has been fielded." [Saleh, 2009]
- Design *Process* Flexibility: "Denotes a willingness and an ability to accommodate requirement changes during the design process (i.e. before the system is fielded), and it characterises either the interaction between the customers and designers … or between different teams of designers working on separate subsystems of a complex engineering design" [Saleh, 2009]

Scouring the literature on flexibility, we find that all remotely viable definitions do share the common element of change. However, not all definitions agree that it must be the system that undergoes change in order for it to be deemed flexible. Moreover, the nature of the change, its source, when it occurs, and how it occurs are all potentially differentiating elements of the published definitions. We do find, though, that the elements of the flexibility definitions can generally be wholly described by the answers to one or more (usually more) of the following five questions:

1. Will the System Change? This refers to whether the system under consideration must change in some manner to be considered flexible. The alternative is that the system does not necessarily change itself, but rather "accommodates" the instigating change.
2. What Measure(s) of Change Efficiency Applies? This aspect of the definition provides a description of how efficient the system change is, relative to resources like time and money.
3. What is the Source of the Change? Asking this tells us where the instigating change force is relative to the system, i.e., internal or external.
4. Is the Change Foreseeable? Aims to capture whether the potential change is one that can be anticipated.
5. When may the Change Occur? This question relates to when in the system's lifecycle it may be exposed to the change, with the delineation being whether the change occurs before or after the system is fielded.

Table 1 provides a summary of all the definitions of flexibility binned according to the five-question template. While adaptability may be the term most often confused with flexibility, it is certainly not the only one. The relationship between flexibility and robustness can be muddled as well. One scholar asserts that "robustness" and "adaptability" are the two design components that enable a system to have flexible performance [Olewnik, 2001]. Table 2 shows a similar summary of the definitions of adaptability, and the summary of the robustness definitions is provided in Table 3. Several other "ilities" and their relationship with flexibility are discussed in detail in the Appendix.

Before the value of flexibility can be ascertained, one needs to quantify flexibility or develop metrics that can be then mapped on the value functions. Several measures have been proposed in literature to quantify flexibility based on decision theoretic principles, ranging from counting number of choices, options, or systems states affected, graph theoretic measures, to Shannon-Weaver type entropy measures, and uncertainty and dispersion measures [Buzacott, 1982; Sethi and Sethi, 1990; Deshmukh, et al. 1998]. Other measures of flexibility are based on the methods used to incorporate flexibility in systems, such as interoperability and modularity [Jacques and Colombi, 2009; Ford and Colombi, 2009; Stryker and Jacques, 2010]. Further methods include real options, decision theory, insurance analysis, risk analysis, attribute tradeoff analysis, cost of delay analysis, and product line ROI analysis. They tend to work better for monetized commercial applications than for DoD measures-of-effectiveness.

FLEXIBILITY												
	System Change?		Measure(s) of Change Efficiency		Source of Change			Foreseeable?		When Change Occurs		Other
SOURCE	Yes	Not Necessarily	Quickly	Cost-Effectively	Int	Ext	Reqmnt	Known	Unk	Prior to Fielding	After Fielding	Related Terms
Thomke, 1997	"modifying a product"		"incremental cost and time"		x	x						
Roser, 1999	"change performance"		"minor time and costs"									
Schulz, 1999	"system to be changed"		"changed easily"									Component of Changeability
Bordoloi, 1999	"change states"											Efficiency and Adaptability
Olewnik, 2001	"changes in configuration"		"real-time"			x	x	x	x			Robustness and Adaptability are modes of Flexibility
Palani, 2003	"design changes"		"ease" of change									
Nilchiani, 2003	"increasing con-trol capacity"					x			x			
Banerjee, 2004		"support new functions"										
Nilchiani, 2006		"ability to respond"	"timely"	"cost-effective"	x	x						
Qureshi, 2006		"responsive-ness"	"degree of responsiveness"									
Keese, 2007	"redesign"		"quickly"	"inexpen-sively"			x		x			
Ross, 2008	"alterations"					x						
Shah, 2008	"ability to change"					x						Adaptability and Flexibility comprise Changeability
Sivanthi, 2008		"accommodate new reqmnts"					x					
Fitzgerald, 2009	"ability to adapt"							x	x			
Viscito, 2009						x						
Brown, 2009	"change on demand"											Scalability, Evolvability, Maintainability, and Adaptability
Nachtwey, 2009	"facilitates an adaptation"		"effective and efficient"			x						Flexible system must be Robust and Adaptable
Saleh, 2009	"modified"		"timely"	"cost-effective"			x	x	x		x	
Lafleur, 2010	"modify a system"		"easily modify"			x	x				x	
Merriam Webster, 2010	"capability to adapt"		"ready"				x					

Table 1: Summary of Flexibility Definitions

ADAPTABILITY										
	System Change?		Source of Change			Foreseeable?		When Change Occurs		Other
SOURCE	Yes	Not Necessarily	Int	Ext	Reqmnt	Known	Unk	Real-time	Offline	Related Terms
Schulz, 1999	"adapt itself"			x				(in operations)		Robustness is a prerequisite of Adaptability
Bordoloi, 1999	"change states"									
Olewnik, 2001	"enhance performance"			x	x	x		x	x	Robustness and Adaptability are modes of Flexibility
Haubelt, 2002	"react to changes"			x				x		
Chung, 2004		"accommodate changes"		x						
Ross, 2008	"alterations"		x							
Shah, 2008	"ability to change"		x							
Brown, 2008	"ability to reconfigure"		x					(in operations)		Reconfigurability or Versatility

Table 2: Summary of Adaptability Definitions

ROBUSTNESS									
	System Change?		Source of Change		Foreseeable?		When Change Occurs		Other
SOURCE	Yes	No	Int	Ext	Known	Unk	Prior to Fielding	After Fielding	Related Terms
Phadke, 1989		minimize effect on performance		x		x		x	
Schulz, 1999		"deliver their intended functionality"		x				x	
Olewnik, 2001		"accommodating change"		x		x		x	Robustness and Adaptability are modes of Flexibility
Carlson, 2002		maintain desired system characteristics	x	x					
Saleh, 2003		"fixed set of reqmnts"	x	x		x		x	
Banerjee, 2004		"fixed behavior"		x		x			
Ross, 2006		"remain constant"		x					
Ross, 2008		"remain constant"	x	x					
Shah, 2008		"continue delivering value"		x					
Saleh, 2009		"fixed set of reqmnts"	x	x					Resistance to Immunity to Change
Brown, 2009		"maintain functionality"				x			Consists of Reliability, Survivability, Resilience to Fragility, and Fault Tolerance
Merriam-Webster, 2010		"performing without failure"	x	x					

Table 3: Summary of Robustness Definitions

2.2 Value of Flexibility

With a sense of what flexibility is, and how it relates to the associated system terminology, we now consider the value of flexibility and why it is needed. Flexibility is widely regarded as a beneficial system characteristic [Fitzgerald, 2009; Thomke, 1998; Bordoloi, 1999; Kumar, 1999; Saleh, 2001; Thomke, 1997; Schulz, 1999]. The basic catalyst for flexibility is system responsiveness. Its value is couched in terms of being able to increase the likelihood of responding to changes more rapidly and at lower cost. Following qualitative statements are found in literature on the dimensions of value of flexibility:

- "is very critical in addressing changing customer needs" [Banerjee, 2004]
- "[is] essential to lowering risk and reducing the cost and length of product development" [General Accounting Office 2001]
- "is of exceptional value; it allows firms to invest less time and fewer resources on activities aimed at minimizing risk" [Thomke, 1997]
- is suitable for "shorter life-cycles of the products and technologies" and "shorter delivery times" [Nilchiani, 2003]
- "plays a significant role in responding faster to customer feedbacks by allowing quicker updates in the products" [Rajan, 2003]
- is needed "when the system's technology base evolves on time scales considerably shorter than the system's design lifetime, thus requiring a solution for mitigating risks associated with technology obsolescence." [Saleh, 2009]
- provides the benefits of "technology insertion throughout the entire system life-cycle … upgrade opportunities and the ease of customization … rapid responsiveness to emerging and changing markets … reduced life cycle cost" [Schulz, 1999]
- "allows firms to invest less time and fewer resources on activities aimed at minimizing risk" [Thomke, 1997]

Flexibility is also described as providing the opportunity "to make (late) design changes that lead to better design solutions with respect to customer needs" and to "pursue a more efficient development strategy that can tolerate a higher risk of design changes [Thomke, 1997]. Flexibility also contributes to "achieving higher levels of performance" [Rajan, 2003], "increased customization" [Nilchiani, 2003], and "superior system capabilities" [Schulz, 1999], and can "eliminate performance tradeoffs" [Olewnik, 2006]. Moreover, flexibility may even extend the life of the system, being described as an "antidote to obsolescence" due to its ability to keep pace with changes [Saleh, 2009].

Despite the widespread affirmation of flexibility and its lauded ability to improve system responsiveness, no sources could be found that provided any sort of quantification of the cited benefit. This is, perhaps, to be expected given that the definitions of flexibility are so divergent, and generally do not allow for such a question to have meaning. In other

words, how can we say how much time and money was saved by our flexible design if we can't even say how flexible the design was?

For now, it's important to understand under what conditions flexibility has value. Note that most value judgments referred to indefinite concepts like change, risk, and evolution. The common element to all assessments of flexibility's value lies in the principle of uncertainty. Several sources made this observation, and all agreed that the value of flexibility is greater under uncertainty [Thomke, 1997; Gershenson, 2003; Rajan, 2005; Saleh, 2009; Shah, 2008], and that the greater the uncertainty, the greater the value of flexibility [Suh, 2007; Hayes, 2006; Krishnan,. 2002; Haubelt, 2002; Hutchinson, 1989]. Krishnan [2002] discusses the value of flexibility in the face of technology uncertainty. Nilchiani [2003] and Saleh [2001] go a step further and insist that flexibility is precisely what is required in order to cope with uncertainty. Hastings [2006] conceives of a four-category design framework intended to mitigate uncertainty in complex systems. The framework begins with sources of "uncertainty," passes through "risks/opportunities" and "mitigations," culminating in possible "outcomes" like reliability, robustness, versatility, flexibility, and interoperability. For Hastings, flexibility is one of several system attributes necessary to contend with uncertainty.

The reasons why flexibility is vital in the face of uncertainty should be clear. System development is a dynamic endeavor, typically consisting of a host of changing variables, including market volatility, personnel turnover, requirement creep, new laws and regulations, budget fluctuations, technological breakthroughs, test failures, etc. A standard mitigation technique to deal with uncertainty is to postpone difficult decisions, and keep the maximum number of options open for as long as possible. Flexibility can allow a program to do exactly that, thereby improving the likelihood of a more optimal decision [Brown, 2008; Gershenson, 2003].

The Cost of Flexibility: The central maxim of economic theory, the no-free-lunch theorem, is always applicable to systems engineering, conveying the important point that it is generally necessary to tradeoff certain goals against others. As valuable as flexibility may be, there is bound to be some kind of tradeoff. Identifying and characterizing this tradeoff is vital if we wish to invest in flexibility; however, there is surprisingly little discussion in the literature as to the nature of this tradeoff.

For instance, a metric does not appear to exist for determining how much flexibility costs, though one source implies that flexibility (and modularity) are negatively correlated to performance Ulrich [1999] and another claims that flexibility often leads to over-capacities, with the inference being that resources are squandered [Nachtwey, 2009]. Others, such as Olewnik [2001], Nilchiani [2006], and Eckert [2004] also warn that there are "tradeoffs" when pursuing flexibility, and that there is likely to be a potential "upfront cost." Nachtwey [2009] conceives of this tradeoff "as an insurance premium which is paid at present in order to have a possible advantage in future." Saleh [2009] recognizes that there is bound to be some cost/performance penalty associated with flexibility and proposes a series of questions that warrant further investigation,

e.g., "Are flexibility and optimization competing paradigms for system design? Is flexibility obtained at the cost of some performance penalty, and do flexible designs/systems exhibit a performance gap compared with the alternative optimized designs/systems?" It does not appear that any researcher has taken on these questions. The closest is a single case study conducted in the manufacturing domain where the researcher found that the flexible design cost 34 percent more to implement at first, "but will incur significantly lower switching costs when the vehicle design changes" [Suh, 2007]. This researcher adds, however, that, "the best flexible designs may not increase up-front investment at all."

Another study, commissioned by the Air Force Office of Scientific Research focuses on the idea of decision flexibility. In attempting to answer the question of how much flexibility is enough, they find that "Lots of flexibility is not significantly better than a little flexibility. The impact of flexibility on performance exhibits strong diminishing returns, with most of the benefit realized with relatively limited flexibility." [Hayes, 2006]

If it's true that flexibility is highly valuable, and it's also true that we can't get something for nothing, we must conclude that we must sacrifice something for flexibility. Performance—particularly optimized performance—would appear to be the likely candidate, but the evidence is lacking at this time. We also note that there is—not surprisingly—no discussion regarding the additional challenge of implementing design flexibility for defense acquisition, where all resources expended must be justified in terms of a validated requirement. Investing additional resources for a design that exceeds an established requirement or may be well suited to accommodate a non-existing requirement is clearly at odds with defense acquisition strategy. Similarly, suggesting that resources should be spent on a nebulous *concept of goodness* like" flexibility" would likely fair no better.

The Need for Flexibility: Just because something has value doesn't necessarily mean that it's worth pursuing. Value is not an absolute concept. For instance, to the individual stranded on a desert island, a million dollars is bound to have less value than a shortwave radio. So the more important question—and the one that represents the central motivation for this study—is should we seek to implement flexibility in defense acquisitions. Based on the academic literature, as well as various government publications, the answer is a resounding "yes."

Consider the following list of potential problems that may be resolved or mitigated through greater flexibility:

- "Complex DoD systems tend to be designed to deliver optimal performance within a narrow set of initial requirements and operating conditions at the time of design. This usually results in the delivery of point-solution systems that fail to meet emergent requirements throughout their lifecycles, that cannot easily adapt to new threats, that too rapidly become technologically obsolete, or that cannot provide

quick responses to changes in mission and operating conditions." (OSD: RT-18 Task Description)

- "The customer often wants a system to have ilities, but is not willing (or does not know how) to pay for them. Additionally, even though customers often request these types of ilities when acquiring systems, it was unclear how to specify, evaluate, and validate these ilities requirements for systems." [Ross, 2008]
- "A framework that allows for consideration of ilities during conceptual design, including concrete specification of how the ilities are defined, can be quantified and relate to perceived value, would benefit both military and industry" [Ross, 2008]
- "Modern systems engineering requires operating in an ever changing environment within which systems often need to adapt to maintain value delivery and to take advantage of emergent opportunities." [Shah, 2008]
- "There is a need for a comprehensive framework that allows decision-makers to measure the value of flexible systems design in its different dimensions." [Nilchiani, 2006]
- For 2008 DOD programs, "research and development costs are now 42 percent higher than originally estimated and the average delay in delivering initial capabilities has increased to 22 months."[General Accounting Office 2009]

If flexibility could be characterized and implemented correctly, the benefit to government acquisition programs would be almost beyond measure. The current lengthy development timelines and rigid acquisition processes could give way to a new paradigm of quick-response modifications to existing designs or fielded products. The ability to respond more rapidly, in turn, generates a self-reinforcing feedback loop that would reduce the likelihood of a system being exposed to additional sources of change, i.e., evolving customer requirements, new strategic direction, budget shortfalls, and technology obsolescence. Tools to characterize, measure, and implement flexible design solutions would be of value during virtually all phases of system development, including concept definition, analysis of alternatives, source selection, and all program milestones (e.g., SRR, PDR, CDR). The ability to design systems to achieve flexibility could also change the calculus of how we determine when to start a new program vice modifying an existing one. Flexibility could even help reinvent the concept of risk management, and allow programs to see risk as just one aspect of uncertainty that has both negative and positive outcomes that contribute to an overall determination of value [Brown, 2009; Collopy, 2003; Nilchiani, 2006].

2.3 Quantitative Methods for Valuing Flexibility

If we lack consensus on what flexibility is, then it is to be expected that quantifying its value will be that much harder [Bordoloi, 1999]. And while success remains elusive [Brown, 2008; Baykasoğlu, 2009], there have been a surprising number of attempts. Unfortunately, most of these attempts only tackle part of the problem or are highly restricted in their applicability [Rajan, 2005], such that we still lack a robust, effective method to formally quantify the value of flexibility [Saleh, 2003]. Nevertheless, it is

worthwhile to review these efforts so we can better appreciate which ones hold promise, and which ones do not.

Within the topic of valuing flexibility in the foreseeable-change area, there are also two primary cases: flexibility for a single system; and flexibility for a portfolio or product line of similar systems. The Parnas strategy applies to both, but in different ways. For single systems, one can determine or estimate the cost of creating and using a modular design (including its effects on other system attributes such as performance and time-to-deliver). One can then use real-options approaches based on estimates of the probabilities and timing of sources of change, and the cost-of-change savings of having the modular design, to estimate the value of the modular-design approach and return on investment in the modular design [Sullivan et al., 1999; 2001]. Similar work has been done by [Mun, 2002; 2005] and by Baldwin-Clark [2000] and DeNeufville [2001; 2003]. An important factor in using existing real options results in developing a framework for valuing flexibility is that some of the basic assumptions underlying the results, such as fluidity of market and non-correlated events, do not apply in the system flexibility valuation. [Ball, 2007] have developed methods to determine the value of an option when the underlying assumptions do not hold, and the resulting uncertainty may be due to a smart adversary, not just randomness in the environment.

An attractive approach for both valuing and determining flexible designs involves various forms of search and optimization of the design trade space of key design parameters. This has been successfully applied in the DARPA F6 satellite program [Brown-Eremenko, Collopy, 2006; 2007; 2009] and in the MIT Lean Aerospace Initiative [Ross, Ross-Hastings; 2006]. Another candidate approach involves comparative Monte Carlo analyses of change sequences with and without modularization using systems dynamics techniques [Madachy, 2008]. Some further attractive candidate approaches involve monetizing the cost of delay in system fielding due to inadequate design for flexibility, through various value estimating relationships relating time of delivery to organizational value [Huang-Boehm, 2006]; the use of commercially-equivalent value streams [Mun, 2005], and insurance-based valuation approaches [Raz-Shaw, 2001].

There are several parallels between valuing flexibility and valuing insurance or warranty payments. Both flexibility and insurance are hedges against future uncertainty, whether in system performance or intended use. Lian and Deshmukh [2009] have shown that even moderate amounts of flexibility in supply contracts can have significant impact on the overall effectiveness of complex supply chains. Current actuarial and warranty research will be examined to determine the appropriate mapping between methods for optimal pricing of risk in those areas and valuing flexibility in system acquisition setting.

For a portfolio or product line of similar systems, modularizing around foreseeable sources of change involves analyzing the commonalities and variabilities across the product line, and developing reusable components for the common features and plug-in interfaces for the variable features. A good example is the Hewlett Packard product line

experience. For a product line of medical and engineering measurement devices, they reduced their time to delivery from 48 months to 12-14 months by investing in two projects that took 57 and 61 months to develop products whose components could largely be reused in subsequent products [Griss, 1995]. Delayed differentiation and mass customization are often effective design strategies in commercial product lines.

Valuing software product line reuse has been extensively analyzed. Poulin [1997] summarizes the results of a dozen reuse studies, and concludes in general that successful reuse requires an added 50% effort in developing and certifying reusable components, and that reuse without modification costs only 20% of the cost of redeveloping components, and that reuse investments pay off for the development of product lines of at least 3 similar products. Reifer [1997; 2002] reports similar results. The Selby [1988] analysis of about 3000 NASA software modules found that reuse with modification of the components was considerably more expensive, adding 20-50% to the cost of reuse. These results were calibrated to 161 projects in the COCOMO II cost model [Boehm et al, 2000], and extended the Constructive Product Line Investment Model (COPLIMO) [Boehm et al., 2004], which calculates the return on investment across a multi-year maintenance period, and finds even greater rates of return when considering the total cost of ownership of the product line versus developing and maintaining separate products. Total cost of ownership appears to be a convincing monetized way of justifying investments in flexibility via product line reuse for organizations such as DoDCAPE.

Similar product line reuse savings have been found for systems engineering in the calibration of the COSYSMO cost estimation model [Valerdi, 2005; Fortune, 2009]. The use of portfolio risk management [Mun, 2003; 2005] provides another strong perspective on valuing a product line portfolio, which also address the sponsors' interest in determining decision drivers for product line scope decisions. A list of 25 critical decision drivers and success factors for product lines were developed in the DARPA Domain-Specific Software Architectures program [Boehm-Scherlis, 1992]. These were grouped into the categories of architecture determination, architecture/component description, component construction, component composition/assemble, and component interchange. Elaborations and case studies on these and other scope decision drivers are well covered in the book Software Product Lines [Clements-Northrop, 2002].

Most approaches for valuing flexibility depend on good estimation of uncertainty. However, estimating and characterizing uncertainty, even for foreseeable sources of chance, is difficult, especially in systems involving new technologies. [Wortman, 2009; Wortman et al. 1994] have developed approaches based on risk analysis in high stakes wagering games to determine how much information is needed to develop a good-enough characterization of uncertainty that can be used to quantify the value added by given measure of flexibility given known areas of potential change.

2.4 Methods, Processes and Tools for Incorporating Flexibility in Systems

Let's assume we know what flexibility is, and we deem it be valuable. Let's further assume that we can measure its value. Then "all" that remains is the task of implementing it. Fitzgerald [2009] states, "how [flexibility] can be achieved is less obvious." Saleh [2009] is particularly pessimistic: "there is not yet a coherent set of results that demonstrates how to embed flexibility in the design of engineering systems."

The current literature on engineering design does not provide a formal approach towards designing products for flexibility. The reason for this is related to the inherent properties of the mechanical design process. Because the overall function in a mechanical system is achieved through the interactions among many subsystems and components which are often useful only in their exact configuration. Therefore, any structural or functional modifications are very difficult to make in order to adapt the system to the changed conditions. As a result of this typical mechanical systems are designed for a specific operational mode.

There are, however several techniques for enhancing a design with respect to known flexibility. These techniques include modular design, product family development, and platform design. The underlying principle in these techniques is the segmentation of a product [Hashemian, 2005]. Since structural connectivity is an inherent property of mechanical systems, in order to reduce propagation of changes the choice is limited to two categories: use of alternative technologies, and segmentation of the structure. The first category basically avoids the use of solid components and their associated spatial constraints, and replaces them with hydraulic, electronic and software systems. The second category is based on the premise that in a modular structure modifications are likely to be confined within segments and are less prone to propagating into other segments.

The proposed solution approach follows the second category in order to make a product adaptable. The adaptability has to be build-in during the design stage. The methodology for an 'Adaptable Design' (AD) is to take advantage of available 'forecast' information and design for predetermined adaptations first. This adaptability is categorized as Specific AD; these methods design products for versatility, upgrading, variety, and customization. The second step then is to design for General AD, which is the design for 'unforeseen' changes. General AD involves fundamental research in design theory and methodology in order to develop practical design methods and guidelines. Hashemian proposes the subordination of a system to a rational functional structure as an approach for increasing general adaptability. Meaning, the general design system consists of a hierarchical assembly of autonomous functional modules.

A similar model is proposed by Gu et al. [2004]. They argue that the most effective way to increase the general adaptability of a product is through the use of a 'segregated

architecture' (clustering and modularization). This will prevent the change in one place of the product to propagate into the rest of the product. They formulate general design guidelines based on functions independence. In addition to these guidelines they also develop a measure of adaptability for products. The developed adaptability factor represents the normalized savings achieved by adaptation versus dedicated product. This measure is applicable to new as well as existing designs.

The work by Willems et al. [2004] focuses on the research question of how adaptable/flexible a design is. Given a product design, new or existing, they develop a dedicated methodology for assessing the adaptability of a product (MAAP). Similar to the work by Hashemian and Gu is the work by Chmarra et al. [2008]. However, their focus is mainly on the specific adaptability, which is related to predictable/anticipated events. They also propose the use of modular design to achieve adaptability without change propagation throughout the entire product. As stated before, prediction of such change and its propagation would be of great help when (re)designing complex products. Presently, the nature and extent of change propagation is neither completely understood nor predictable. Clarkson et al. [2001] shows that Design Structure Matrices (DSM), known design method used to store information about connections between components and modules in the product, can be used to provide indication as how change may propagate through a product. The proposed mathematical model by Clarkson et al. can be used to predict the risk of change propagation in terms of likelihood and impact of change.

A similar model to determine change propagation is developed by Arts et al. [2008]. They formulate a method to cluster components of an adaptable system based on Design Structure Matrices (DSM). For each scenario or action plan to perform adaptability, the importance of component interconnections is rated in a separate DSM structure. Based on the original DSM and the adaptability DSM components can be grouped together.

Similar research is found in the work by Cervantes et al. [2004] and Wilke[2008]. They both propose the use of a component/modular based approach. Cervantes et al. develops a service oriented component model that is capable of autonomously adapting at runtime due to the dynamic availability of the services provided by constituent components. Wilkes model is based on an intelligent multi-agent-system that enables the system to react on events autonomously.

An additional approach of autonomous system change is developed by Berthelot et al. [2008]. They propose an automatic design generation methodology, based on an adequation algorithm architecture (AAA) methodology. Its aim is to consider simultaneously architecture and application algorithm, both are described by graphs, to obtain an optimized implementation for heterogeneous architectures based on field-programmable gate arrays (FPGAs). The purpose of this methodology is to ease and speed up the run-time reconfiguration (RTR) implementation.

Besides the above listed stream of research there is a second stream of research that focuses on as to what extent a product should be made adaptable in order to keep the product profitable/usable. An early example of a flexible design approach is the work by Roser et al. [1999]. They propose an extension of the robust design solution by adding flexibility to the design process. The reason behind the extension of a robust design is related to the fact the robustness only deals with random noise. The flexible design approach differs from the robust design approach by trying to achieve greater performance and improved utility, accepting the risk of design changes. The methodology applied in the model by Roser et al uses a conservative error proof design, which can be created by combining the noise and the error distribution, to evaluate and optimize the flexibility of the actual design.

In later research such as the one by Olewnik et al. [2006] the goal is to aid in the development of a decision support framework that maximizes corporate utility while setting attribute and budget constraints for the conceptual design phase. This framework draws on concepts from multi-objective optimization, consumer choice theory, and utility theory. They suggest that by monitoring how the changes in the levels of adaptability/robustness affect flexibility, it may be possible to gain insight into the difficulties of mapping between the performance and design spaces.

Other research focuses on how to design to maintain the competitive advantage despite environmental change. The work by Mark [2005] develops a framework to increase the system's flexibility by adapting the art of platforming. This type of flexible system will enable the customer to exchange any old/obsolete component for a component that is needed to coop with an environmental change. Flexibility of this type of system is then measured as the performance increase (output) corresponding to the required cost and time to realize the change. Similar work to Mark is that of Cormier et al. [2008]. However, instead of focusing on the consumer, in terms of providing a flexible product or flexible design, Cormier et al. focuses on the design flexibility. This design flexibility will allow the engineer to adapt a product under changing market conditions. This for instance will allow them to customize products based on customer need and requirements. They develop a metric to assist with the evaluation of design options early on in the design process by rating the overall flexibility of the system using flow analysis tables.

The focus of Chens [1999] work is on providing flexibility in the design process by looking for a range of solutions that involve information passing between players. Rather than focusing on a single point solution in one disciplines model they include multiple designs for the performance evaluation. Similar to Chens work, Li et al. [2004] focuses on information sharing. They develop an Internet-enabled system to support collaborative and concurrent engineering (CE) design in order to share domain knowledge between designers and systems. The approach is based on the seamless integrating of three functional modules, i.e., co-design, Web-based visualization and manufacturing analysis for designers to conduct CE methodology through invoking distributed services.

All of the above mentioned MPTs have one deficiency in common. There is no analytical approach to supporting the decision process of selecting a particular process of implementing flexibility. The work by Schulz et al. [1999] provides an attempt to answers the question as to why, when and where, what, and how changeability should be incorporated into a systems architecture. However, their framework of design principals falls short on the analytical justification of selecting one principle over another.

The same goal to focus on flexibility implementation is found in the work by Bartolomei et al. [2008] . They identify key system aspects that should be addressed for leveraging flexibility. The approach to identify these key system aspects is based on real option opportunities.

Furthermore, from reviewing the current literature it becomes apparent that the actual implementation of flexibility at the system level is very limited. This is mostly due to physical limitations at the design stage.

3 EVALUATION OF CURRENT CAPABILITY TO VALUE FLEXIBILITY

We now present three approaches for valuing flexibility, show their applicability using domain driven case studies, and compare their strengths and weaknesses.

3.1 Total Ownership Cost (TOC) Approach

In the DoD context, Total Ownership Cost (TOC) includes the costs to research, develop, acquire, own, operate, and dispose of a system [Boudreau-Naegle, 2003]. The Weapon System Acquisition Reform Act of 2009 [WSARA 2009] establishes a DoD Director of Cost Analysis and Program Evaluation (CAPE), whose cost analysis scope includes "full consideration of life-cycle management and sustainability costs in major defense acquisition programs and major automated information systems." DoD Instruction 5000.02, Enclosure 7, establishes DoD acquisition policy that the Cost Analysis Improvement Group (CAIG) within the CAPE organization "shall prepare independent Life Cycle Cost Estimates (LCCEs) per section 2434 of Title 10, United States Code. ... The Milestone Decision Authority shall consider the LCCE before approving entry into the Engineering and Manufacturing Development (EMD) Phase or the Production and Deployment Phase" [USD(AT&L), 2008].

As a result of being required as part of the DoD acquisition process, a TOC approach provides an acquisition decision-relevant way to determine appropriate levels of investments in flexibility. When representative data is available, this can be done by determining the relative costs of system development, operations, and support with and without the flexibility investments over a given system life span. The major sources of added ownership cost due to shortfalls in flexibility are rework during development, adaptation to change during operations and support, and duplication of effort in developing and supporting similar systems.

3.1.1 ADVANTAGES, CHALLENGES, AND STRATEGIES FOR THE TOC APPROACH TO VALUING FLEXIBILITY

TOC Advantages for Valuing Flexibility

Besides being required by law and DoD policy, the TOC approach has several advantages with respect to alternative methods such as real options, insurance-based, and risk-based approaches. It is easy to understand, has clear cause-and-effect

relationships, can be used to complement and contextualize alternative methods, and can be tailored to particular domains.

It is easy to understand across various acquisition stakeholders (program managers, oversight managers, systems engineers, cost analysts, contract managers, warfighters) because its costs (investments in reducing downstream rework, change processing, and duplication of effort) and benefits (the effects of the investments on TOC) are expressed in simple arithmetic formulas as compared to complex mathematical formulas and probabilistic assumptions. Its cause-effect relationships (the investments and their effects on reducing downstream rework, change processing, and duplication of effort) are straightforward and can be calibrated to project data. It can be used either in standalone mode or to complement and contextualize alternative methods such as real options, insurance-based, and risk-based approaches. And once experience and data are available in particular domains, their relative investment costs and ownership costs can be more accurately calibrated and related to domain-specific cost drivers and decision alternatives.

TOC Challenges

The primary challenges involved in TOC analysis involve various "devils in the details" in estimating flexibility investment costs and their resulting cost savings, and in predicting uncertain futures.

Flexibility investment costs for individual systems include the costs involved in designing, developing, and evolving systems to ensure continuing diagnosability, accessibility, replacability, low logistic costs, code understandability and modularization around anticipated sources of change. These added costs may be more than the added costs of design, development, and evolution, as there may be additional costs involved in tradeoffs between achieving flexibility and achieving other desired attributes such as performance, dependability, usability, size, weight, and power consumption. Similar challenges are involved in estimating the resulting benefits.

Such tradeoffs among desired levels of service or "ilities" are classic challenges in systems engineering. Once rough models for determining such tradeoffs are available, though, they can be calibrated and extended as measured experience is built up.

Flexibility investment costs for product lines include the costs of domain engineering to characterize the commonalities and variabilities across the domain; the costs of determining how broad a scope across which to develop and maintain a product line; the costs of developing more reusable components; the costs of verifying that the reusable components will operate satisfactorily across the product line; the costs of operating a repository of reusable components; and the costs of evolving the product line architecture and the reusable components [Boehm-Scherlis, 1992; Poulin, 1998]. Again, the costs may include effects of tradeoffs between product line generality and other desired –ilities. The resulting cost savings will depend on the relative costs of the

commonalities and the variabilities, which may not be constant across the product line, and the degree to which the commonalities result in components that can be reused without modification (black-box) or which require some modification (white or glass box). The effects of evolution of reusable COTS or purchased services involve more effort that reduces the benefits.

A final challenge is the difficulty of predicting the useful lifetime of reuse architectures and reusable components in a world of rapid change. Again, though, once rough models for determining such effects are available, they can be calibrated and extended as measured experience is built up.

Strategies to Address TOC Challenges

An important strategy is to develop concepts of operation for the use of the TOC models in DoD decision situations, and to prioritize model capabilities that best support the decision situations. Our initial concept of operation is one in which DoD leadership is evaluating a proposed system development approach as part of the guidance in DoDI 5000.02, and wishes to determine how well the proposers have analyzed the alternatives of building in single-system flexibility or of developing a product line of similar systems, in terms of DoD total ownership costs. Other concepts of operation involve internal decisions of determining how much single-system flexibility or product-line breadth is enough; performing tradeoffs among flexibility and additional -ilities; and decisions to replace inflexible legacy systems with more flexible ones.

A particular key strategy is to tailor analysis approaches to common situations. These generally involve domain analysis, which is one of the elements of determining the system's or product line's domain architecture. Others involve decisions on whether and to what extent to use commercial-off-the-shelf (COTS) components, open source components, and government-furnished components.

Another strategy involves the development and evolution of parametric estimation models for investment costs and resulting ownership costs as a function of investment effectiveness. Once these are available, they can be continually improved via data collection and analysis.

The sections below provide example models which have been calibrated to DoD-representative project data that can be used as starters for such continuous improvement. The current data is software-intensive system data available at USC. We are working with AFIT and NPS to obtain counterpart hardware data, initially with AFIT on modular munitions, and with NPS on ShipMain maintenance data.

Initial Analysis Focus: Largely Predictable Change; Individual Systems and Product Lines

Our initial analysis focus is on two simple tools for valuing flexibility via TOC analysis for two primary cases in which some of the sources of development rework and of post-development adaptation to change are relatively predictable. The first case is for an individual system in which common sources of change can be anticipated and approaches for facilitating the sources of change can be invested in. For hardware-intensive systems, this is covered under design for maintainability [Blanchard et al., 1995], including considerations of diagnosability, accessibility, replacability, and logistic cost tradeoffs. For software-intensive systems, diagnosability is also important, but other factors such as code understandability and modularization around anticipated sources of change are also critical [Lehman-Belady, 1985; Parnas, 1979]. The general effect of such strategies is shown in Figure 1, which shows the exponential growth in cost to make changes vs. time for traditional large TRW systems [Boehm 1981] vs. the larger up-front cost to eliminate risks and design for ease of change, and subsequent flat cost-growth data for the later TRW CCPDS-R project [Royce, 1998].

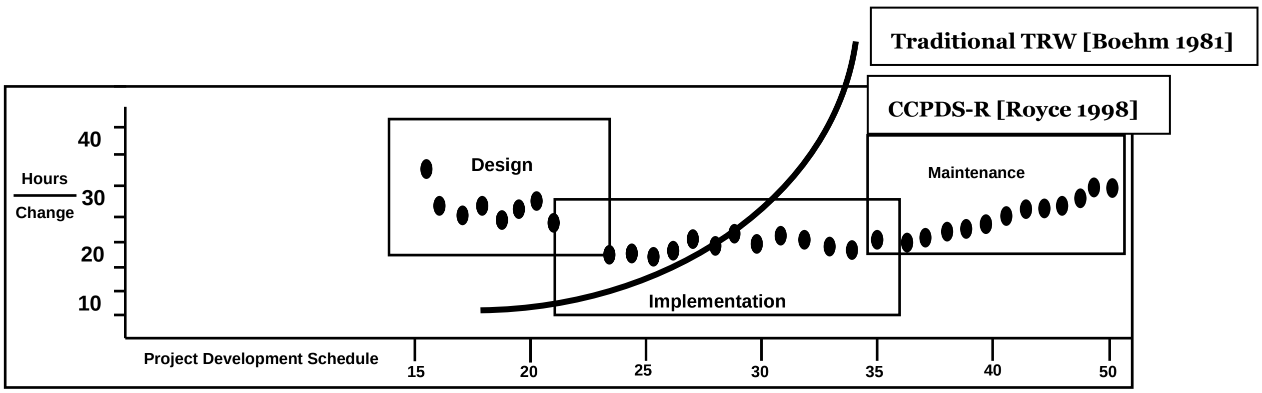


Figure 1: Traditional TRW vs. Change-Architected Cost of Change Growth

The second case is for reuse-driven investments across a family of systems vs. development of individual stovepipe systems. Here, the strategy is basically the same for hardware-intensive and software-intensive systems. For a class of similar products, a systems engineering activity identifies the <u>commonalities</u> among the products, and develops these into reusable infrastructure and components. It also identifies the <u>variabilities</u> among the products, and develops plug-compatible interfaces from the common parts to the variable parts to facilitate integration. The general effect of such strategies is to increase the cost and schedule of the initial projects to include investment in identifying and architecting the common infrastructure and generalizing the common parts for product line use, but to significantly reduce the costs and schedules of later products in the product line through higher reuse and simpler integration. Figure 2 shows an example from Hewlett-Packard's investment in software reuse across its measurement-box and network-equipment product lines [Griss 1993; Lim 1998].

This Section will elaborate on the overall advantages and challenges of the TOC approach with respect to valuing flexibility in Section 3.1.1, and will then describe

working models and their use in analyzing the TOC and return-on-investment (ROI) effects of the individual-system approach in Section 3.1.2, and of the product line approach in Section 3.1.3.

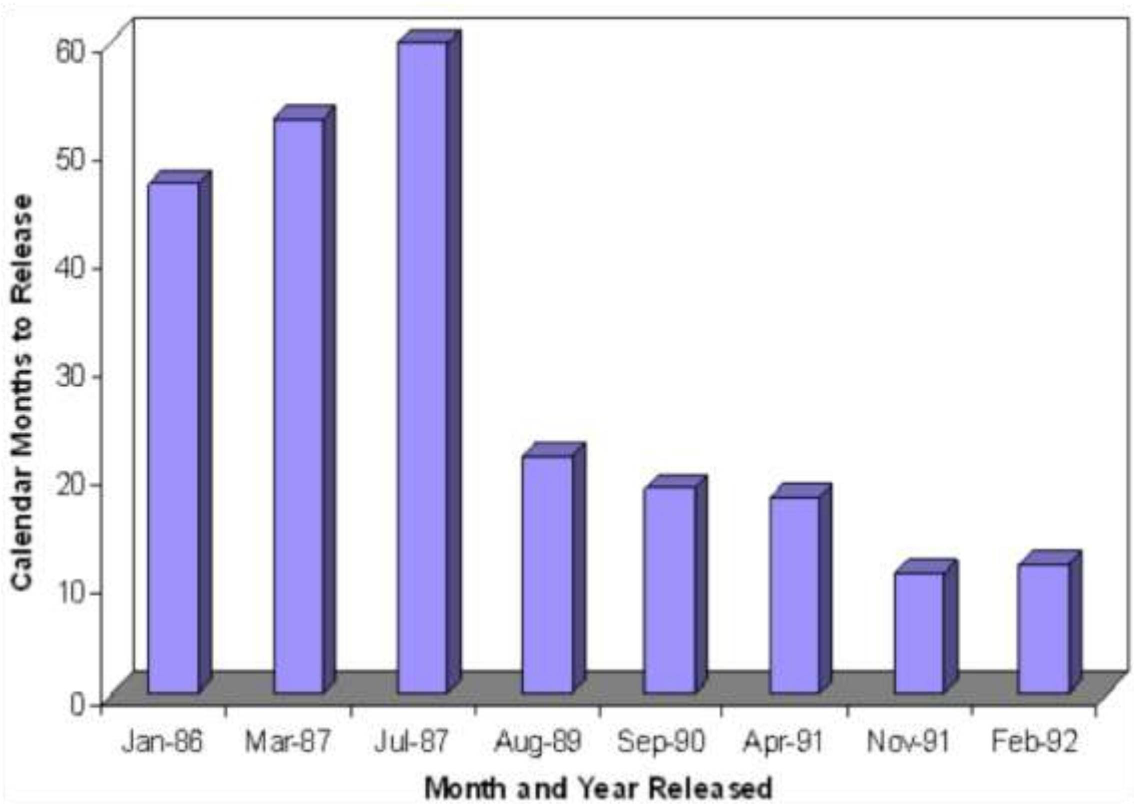


Figure 2: HP Product Line Reuse Investment and Payoff

3.1.2 A TOC MODEL FOR VALUING FLEXIBILITY OF INDIVIDUAL SYSTEMS

Reducing Software Rework via Architecting for Flexibility

Analysis of project defect tracking cost-to-fix data (a major source of rework costs) on representative traditional TRW C4ISR-type projects showed a Pareto effect, as 20% of the defects accounted for 80% of the rework costs, and that these 20% were primarily due to inadequate architecting for flexibility and risk resolution.

For example, in TRW Project A in Figure 3, most of the rework was the result of development of the network operating system to a nominal-case architecture, and finding that the systems engineering of the architecture neglected to address the risk that the operating system architecture would not support the project requirements of successful system fail-over if one or more of the processors in the network failed to function. Once this was discovered during system test, it turned out to be an "architecture-breaker" causing several sources of expensive rework to the already-developed software. A similar "architecture-breaker," the requirement to handle extra-long messages (e.g., full-motion video), was the cause of most of the rework in Project B, whose original nominal-case architecture assumed that almost all messages would be short and easy to handle with a fully packet-switched network architecture.

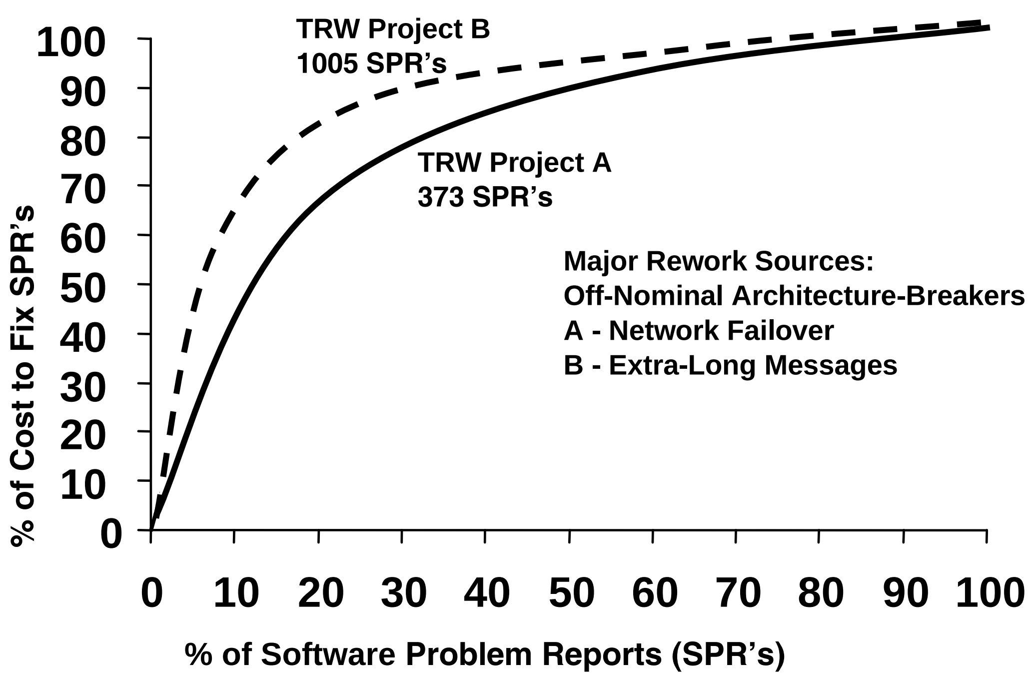


Figure 3: Pareto 80-20 Distribution of Cost-to-Change

Earlier, analyses of cost-to-fix data at IBM[Fagan 1976], GTE [Daly 1977], Bell Labs [Stephenson 1976], and TRW [Boehm 1976] found consistent results showing the high payoff of finding and fixing defects as early as possible. As seen in Figure 4, relative to an effort of 10 units to fix a requirements defect in the Code phase, fixing it in the Requirements phase involved only about 2 units of effort, while fixing it in the Operations phase involved about 100 units of effort, sometimes going as high as 800 units. These results caused TRW to develop policies requiring thorough risk analyses of all requirements by the project's Preliminary Design Review (PDR), including such cost-to-change risks as off-nominal architecture-breakers and user interfaces. With TRW's adoption of the Ada programming language and associated ability to verify the consistency of Ada module specifications, the risk policy was extended into an Ada

Process Model for software, also requiring that the software architecture pass an Ada compiler module consistency check prior to PDR [Royce, 1998], enabling much of systems integration to be done before component development.

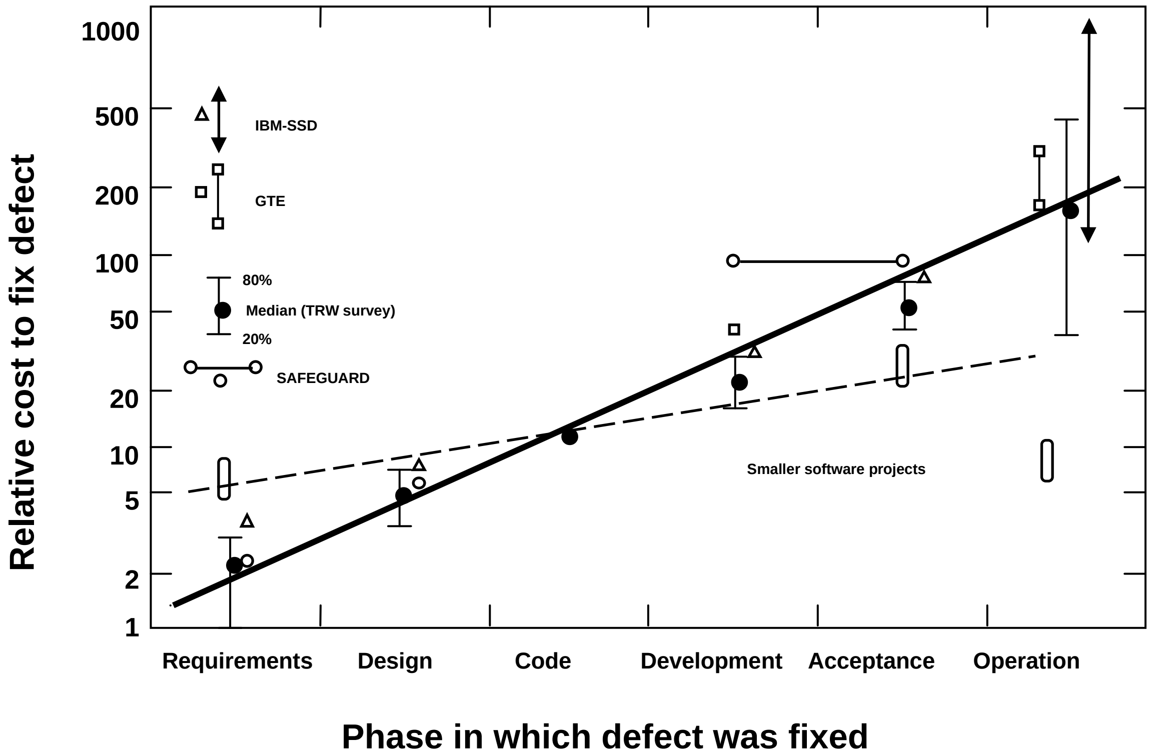


Figure 4: Cost of Change vs. Development Phase, Traditional Sequential Development

A Successful Example: CCPDS-R

This enabled subsequent projects to perform much of systems integration before providing the module specifications to programmers for coding and unit test. As a result of this and the elimination of architecture risks prior to PDR, subsequent projects were able to significantly reduce late architecture-breaker rework and the steep slope of the cost-to-fix curve. A good example was the Command Center Processing and Display System-Replacement (CCPDS-R) project described in [Royce, 1998] whose flattened cost-to-fix curve was shown in Figure 1. It delivered over a million lines of Ada code within its original budget and schedule. Its PDR was held in month 14 of a 35-month initial-delivery schedule and included about 25% of the initial-delivery budget, including development and validation of its working high-risk software, such as its network operating system and the key portions of its user interface software.

Data from Projects A, B, and CCPDS-R have been used to develop and calibrate a model that compares the TOC of projects like A and B which have not been designed for

flexibility, and CCPDS-R, which was designed for flexibility. The model and examples of its use are shown below.

The Total Ownership Cost – Single System(TOC-SS) Model

The simple initial TOC-SS model has the following inputs:

%D – The % of development cost invested in Design for Flexibility

System Size – For software, the equivalent KSLOC (thousands of source lines of code)

- For hardware, the COSYSMO size parameter: complexity-weighted numbers of
- requirements, interfaces, operational scenarios, and algorithms

#F – The number of years that the system undergoes field changes

%FC – The percentage of the fielded system size undergoing change

The TOC-SS model has the following outputs:

TOC (Devel) – The TOC for development

TOC (Devel + K) – TOC (Devel) + TOC (K years of fielding), K = 1, …, #F

The steps in the simple initial TOC-SS model are as follows:

1. For design with and without flexibility, use %D as a proxy for Design for Flexibility to determine the exponent B determining the project's Rework Fraction RF from its size, using the values in the table below. For software, B has been calibrated to 161 projects in COCOMO II [Boehm et al., 2000]. For hardware, we propose to calibrate it from AFIT or NPS data.

%D	5	10	17	25	33	50
B	.0707	.0565	.0424	.0283	.0141	0.0

2. Compute RF = $(\text{Size}^{1+B} - \text{Size}) / \text{Size}$

3. Estimate the project's nominal cost NC from its Size and other parameters. For software, COCOMO II or other cost models can be used. For hardware, cost models such as Price H and SEER-H can be used.

4. Compute TOC (Devel)with and without flexibility from their values of RF and %D as TOC (Devel) = %D + NC * (1 + RF)

5. For K = 1, …, #F, compute TOC (Devel + K) = TOC (Devel) + K * NC* RF

Comparison of Model Results and Projects A, B, and CCPDS-R Data

Figures 5 and 6 below show the results of calculating the relative Total Ownership Costs for Systems A, B, and C (CCPDS-R). For comparison, the values of %Rework (RF*100) for Systems A and B are $100^{1.0707}$– 100 = 38.5% (vs 35.7% and 41,2%), and for CCPDS-R is ($355^{1.0283}$-355)/3.55 = 18% (vs. 13.85%).

	A	B	C	D	E
1	**Input Parameters**	**System**			
2		**A**	**B**	**C**	
3	Software Size (KSLOC)	100	100	355	
4	# Change Requests/Release	373	1005	1600	
5	# Change Requests (I&T only)				
6	# I&T Change Requests/Release/ > 1 PM	27	22		
7	# Total Change Requests/Release/ > 1 PM			16	
8	Change Request Fix Time (See assumption #2)	261	356	263	
9	Total Effort (Person Months)	731	865	1900	
10	% Arch, RESL	5%	5%	25%	
11	% Rework, RVOL	35.70%	41.16%	13.85%	
12					
13	**Cumulative Total Cost of Ownership**	Project A	Project B	Project C	
14	Cycle 1	40.70%	46.16%	38.85%	
15	Cycle 2	76.41%	87.31%	52.70%	
16	Cycle 3	112.11%	128.47%	66.55%	
17	Cycle 4	147.82%	169.62%	80.40%	
18	Cycle 5	183.52%	210.78%	94.25%	

Figure 5: TOC Calculations for Projects A, B, and C (CCPDS-R)

Figure 6 shows the results graphically. Thus, the model can be used in an acquisition decision situation to show that if a project proposes a hastily-designed, inflexible point solution and has not done an analysis of the alternative of investing in determining its primary sources of change and designing to confine these within system components, the project's TOC will represent a significantly higher cost to DoD and the taxpayers.

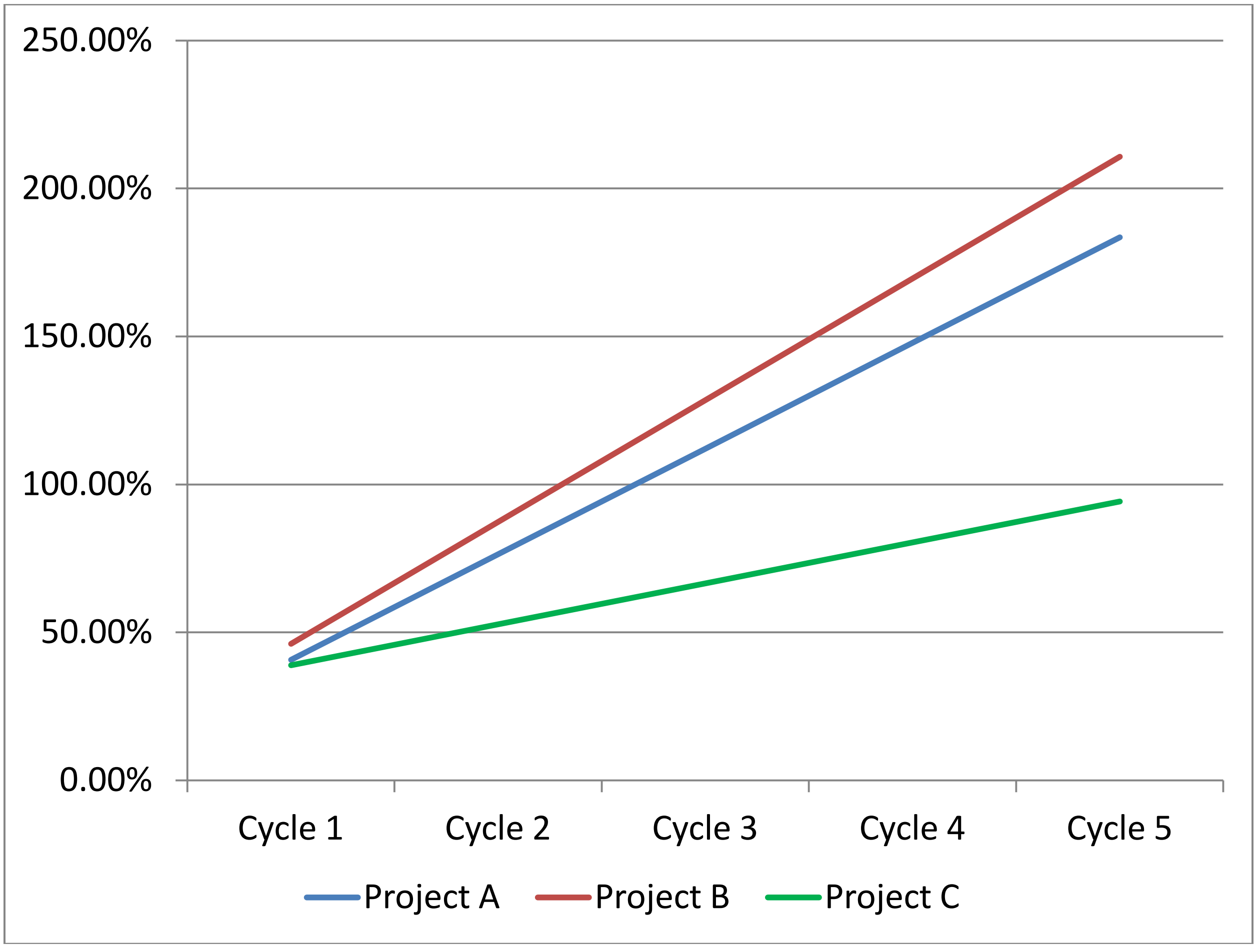


Figure 6: TOC's for Projects A, B, and C (CCPDS-R) Relative to Baseline Costs

3.1.3 THE TOC MODEL FOR VALUING FLEXIBILITY OF PRODUCT LINES

This approach is a TOC analysis for a family of systems. The value of investing in product-line flexibility using Return-On-Investment (ROI) and TOC is assessed with parametric models adapted from the Constructive Product Line Investment Model (COPLIMO) [Boehm et al., 2004]. COPLIMO is based on the well-calibrated COCOMO II model [Boehm et al., 2000] with 161 data points. The new models are implemented in separate tools:

- System-level product line flexibility investment model.
- Software product line flexibility investment model. The detailed software model includes schedule time with NPV calculations.

Figure 7 shows the inputs and outputs for the system-level product line model.

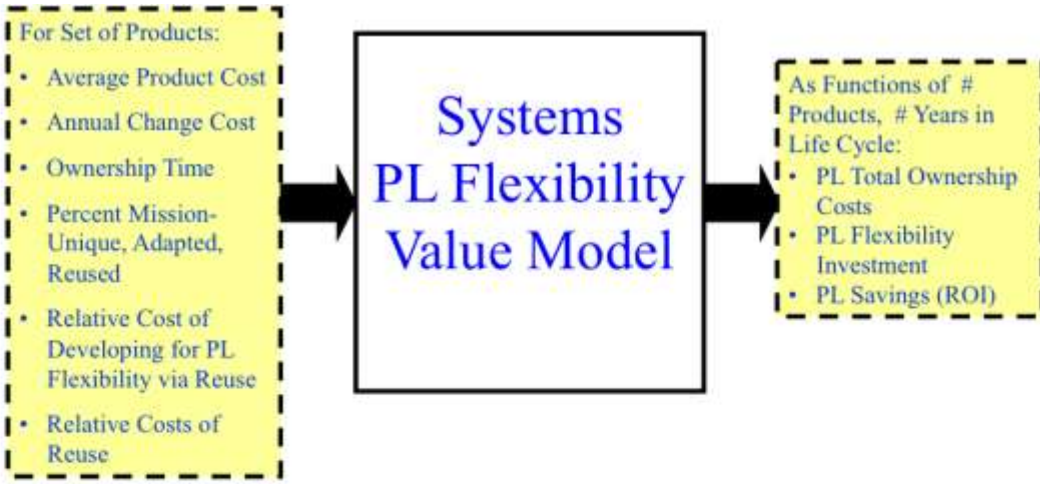


Figure 7: Systems product line flexibility value model (TOC-PL).

The cost of the first system is determined by multiplying the average product cost by the fraction of the product to be developed for reuse, (%Adapted + %Reused)/100, multiplying that by the relative cost of developing for product line flexibility reuse, and adding that to the system-unique cost (%Unique * Average Product Cost / 100) which does not have to be developed for reuse. For subsequent products, the cost of the unique system portion is the same, but the equivalent costs of adapted and reused portions are determined by their relative costs of reuse. For hardware, the relative costs of reuse should include not only the cost of adapting the reused components, but also the carrying costs of the inventory of reusable components kept in stock.

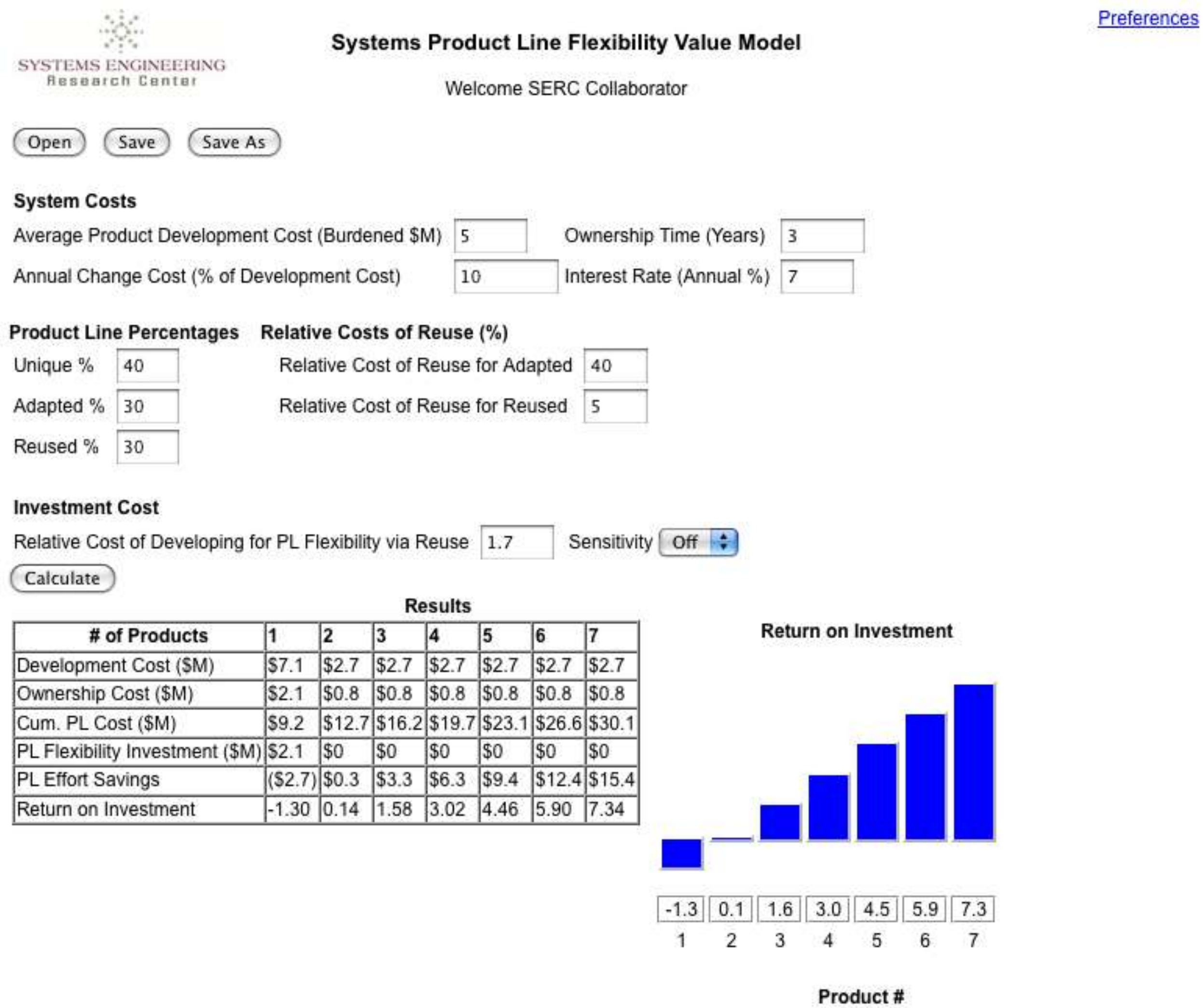
The net effort savings for the product line are the cost of developing separate products (#Products*Average Product Cost) minus the total cost of developing Product 1 for reuse plus developing the rest of the products with reuse. The ROI for a system family is the net effort savings divided by the product line flexibility investment, (Average Product Cost) * (%Adapted + %Reused) * (Relative Cost of Reuse + Carrying Cost Fraction – 1)/100. The TOC is computed for the total lifespan of the systems and normalized to net present value at specified interest rates.

The tools are available for SERC use with a file system, and are awaiting clearance for public distribution.

3.1.4 Quantitative Evaluation of Flexibility Using a Case Study

The case shown below represents a family of seven related systems with three-year ownership durations. It is assumed annual changes are 10% of the development cost. Within the family of systems, each is comprised of 40% unique functionality, 30% adapted from the product line and 30% reused as-is without changes. Their relative costs are 40% for adapted functionality and 5% for reused. The up-front investment cost in flexibility of 1.7 represents 70% additional effort compared to not developing for

flexibility across multiple systems. Figure 8 shows the consolidated TOC and ROI outputs.



# of Products	1	2	3	4	5	6	7
Development Cost ($M)	$7.1	$2.7	$2.7	$2.7	$2.7	$2.7	$2.7
Ownership Cost ($M)	$2.1	$0.8	$0.8	$0.8	$0.8	$0.8	$0.8
Cum. PL Cost ($M)	$9.2	$12.7	$16.2	$19.7	$23.1	$26.6	$30.1
PL Flexibility Investment ($M)	$2.1	$0	$0	$0	$0	$0	$0
PL Effort Savings	($2.7)	$0.3	$3.3	$6.3	$9.4	$12.4	$15.4
Return on Investment	-1.30	0.14	1.58	3.02	4.46	5.90	7.34

Figure 8: Product line flexibility TOC and ROI results.

However, it is desired to evaluate ranges of options and assess the sensitivity of TOC. The tools allow for a range of relative costs as shown in Figure 9 for sensitivity runs. The results show that the model can help projects determine "how much product line investment is enough" for their particular situation. In the Figure 9 situation, the best level of investment in developing for reuse is an added 60%.

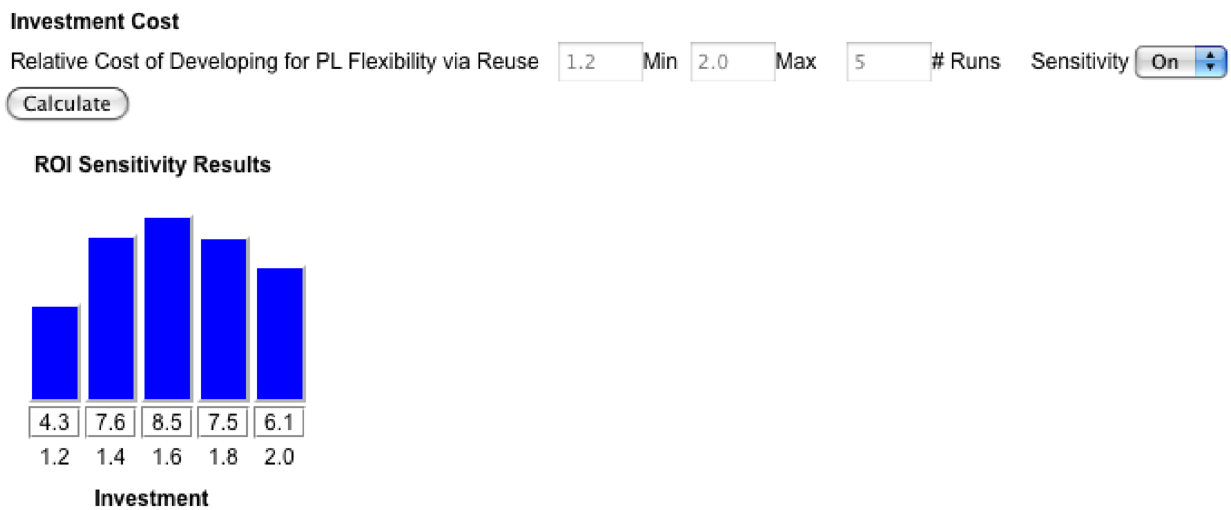


Figure 9: Example sensitivity analysis (ROI only).

Other types of sensitivity analyses can be conducted. Figure 10 shows example results of assessing the sensitivity of TOC across a range of product ownership durations. Most product line cost estimation models focus just on development savings, and underestimate the savings in Total Ownership Costs.

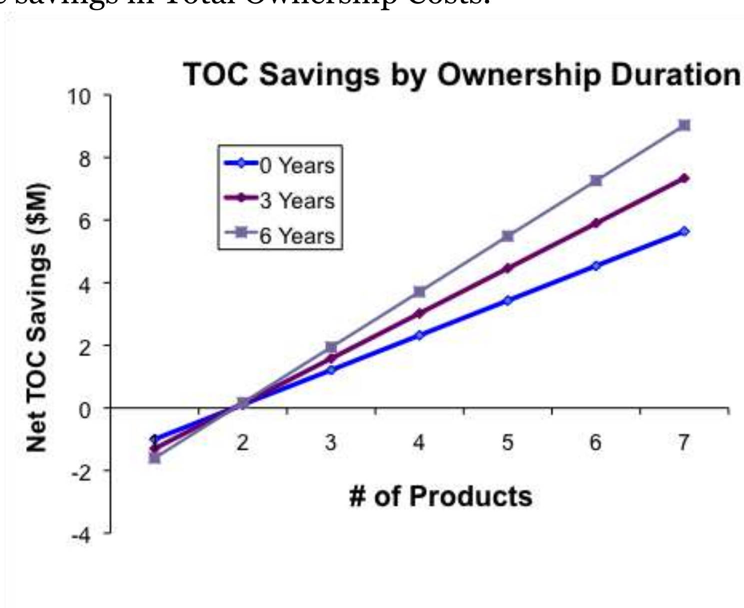


Figure 10: TOC-PL sensitivity by ownership duration results.

The TOC-PL model can also be used in an acquisition decision situation to show that if a project proposes a stovepipe single-product point solution in an area having numerous similar products, and has not done an analysis of the alternative of investing in a product line approach, the project's TOC will represent a significantly higher cost to DoD and the taxpayers.

3.1.5 Proposed Next Steps

Even in their current simple forms, the TOC-SS and TOC-PL models provide strong capabilities for analyzing alternative approaches to system acquisition and the effects on TOC. We plan to work with AFIT and NPS personnel and data such as Modular Munitions and ShipMain data to calibrate and refine the models to better address hardware-intensive systems. Depending on sponsor priorities, there are several further extensions to the models that could add value in various situations. The TOC-SS model could address situations in which annual change traffic varies by year or by system element, provide present value calculations (done in TOC-PL), provide special domain-specific models, or investigate complementary strategies such as investigating key personnel strategies, use of COTS products or purchased services. Similar extensions could be added to the TOC-PL model, including effects of varying product sizes, change rates, product line investment costs, and degrees of reuse across the products in the product line. The models could be combined with each other or with complementary models involving real options, risk assessments, or tradeoffs among flexibility aspects such as evolvability, interoperability, portability, or reconfigurability; or between flexibility aspects and other –ilities such as security, safety, performance, reliability, and availability.

More ambitious extensions could address aspects of complex adaptive systems to address unforeseeable sources of change, such as monitoring change traffic to determine changes or patterns in system hot-spots and ways to adapt the system to better deal with them, or to address complementary adaptive approaches such as autonomous logistics or monitoring of threat patterns.

3.1.6 Strengths and Weaknesses

Strengths

- Simple approach
- Including future uncertainty in decision
- Cooperating with the neoclassical theory of investment, which states when the marginal cost and marginal revenue are identical, the efficiency of economics in achieved.

Weaknesses

- Estimating future cash flow is problematic.
- How the discount rate is determined is controversial.
- The attempt to overcome these 2 disadvantages is TCO or expanded NPV

- NPV approach implicitly assumes reversible decision. Reversible investment means the investment can be undone and the expenditures recovered. However in the real world many decisions are irreversible.
- NPV approach is appropriate for 'now or never' decision.

3.2 Hedge Framework

3.2.1 Overview of the Approach

The University of Virginia (UVa) team is developing and evaluating novel approaches to creating, modeling, valuing and exploiting flexibility in system design and development.

The guiding assumption is that the goal of the decision maker is to obtain the greatest value possible for one's investment in a system. The question is, where does value come from, and how can one reason systematically to optimize for value?

Value in UVa's view is measured by a rational and well informed actor's willingness to pay for an asset in a given environment. The role of the environment in this model is crucial. UVa's framework thus emphasizes the need to model the assumed environment when reasoning about value.

The next question is, what is the value of an engineering system and where does it come from? In UVa's framework, the value of a system derives from two basic sources: the set of capabilities that the system provides and the set of opportunities that it provides.

A capability describes what a system can do as is. An opportunity is the possibility to invest additional resources to change a system into a new system – as it could be. To exercise an opportunity—to actually make such a change—incurs some cost and yields a system with a modified capability and/or opportunity set. The changes in capabilities and/or opportunities generally then change the value of the system.

We can now state two key premises of this work. First, the opportunity set that a system provides—the possibilities a system affords for follow-on investments in new capabilities or improved performance or in other improvements—can have enormous value. Indeed, its value can far exceed that of its capabilities, even in cases in which no opportunity can be taken for immediate or certain profit. Second, it is not enough to have opportunities. One must also exercise effectively the opportunities that one has manner to realize their potential value.

These observations then lead to two specific questions for which we seek constructive answers. First, what important set of opportunities (i.e., what flexibility) does a system provide and what is it worth in a given environment? Second, given an opportunity set in a changing environment, when, if ever does one decide to exploit a given opportunity?

The problem that UVa is addressing is that, while it is relatively easy for decision makers see and value capabilities, it is difficult to see and value opportunities. Capabilities are useful, visible properties of a system as it is. Opportunities, by contrast, are invisible—often rooted in internal details of a system or project, e.g., in a modular architecture--and often have no immediate relevance to system users. Consequently, the opportunity set provided by a systems is often overlooked, its value is underestimated, the system is valued incorrectly, and managerial decisions deliver much less value than possible.

UVa's approach to this problem is to make both opportunity sets and the environments in which they will be valued explicit in system design and engineering. An environment in turn models not only the present “state of nature” but also possible future states.

It is key to value opportunities with respect to environments that include projections about possible future states of nature. First, the present value of an opportunity utterly depends on projections about possible future conditions. Second, we must have a good handle on the present value of an opportunity in order to develop a valid theory about when, if ever, to exercise it. The decision rule in this regard is that one should exercise if and only if the payoff net of investment costs equals or exceeds the present value of the opportunity.

UVa's technical approach is to make key opportunities and environment models explicit during system design and evolution, and thereby subject to both valuation and dynamic management. The valuation of the opportunity sets afforded by a system is our answer to the question what is flexibility and how should it be valued? Dynamic updating of an environment model and enforcement of the aforementioned rule is UVa's answer to the question, given such flexibility, how does one use it to optimize project value over time?

Concretely, UVa is developing these ideas primarily in the context of software systems. In this context, UVa is exploring enhancements to modern software development tools and environments to provide support for explicit representation of sets of opportunities, environments, and valuation functions. In terms of valuation functions, UVa is working on the assumption that there is considerable uncertainty about what specific valuation approaches are best. Therefore, UVa remains somewhat neutral, and is exploring an approach that will accommodate different approaches as modular plug-ins.

To ground the work, UVa is exploring the use of event trees with subjective probabilities to value opportunities created by decisions to delay investments while uncertainties are resolved; and the use of Baldwin and Clark's approach to valuation of the opportunities for low-cost substitution created by modular architectures.

UVa is well aware of theoretical difficulties in assuming that traditional "real options" techniques can be applied to engineering design decisions – approaches that assume replicating portfolios or proxies for such, or that assume specific characteristics of the underlying stochastic payoff processes. The specific valuation approaches that we are exploring are explicitly intended to avoid such difficulties. Indeed, our use of the term opportunity as opposed to option is meant to clearly indicate that we do not propose to adopt a real options approach uncritically.

In sum, UVa views flexibility in terms of opportunities to make investments to change a system in some way. The value of these opportunities, and thus the value of flexibility, is highly sensitive to assumptions about the environment (e.g., willingness of customers to pay for particular capabilities at particular times), including assumptions about possible future states of the environment. The value of flexibility is the value of the opportunities in a design. Beyond assessing such value, decision makers need to have the analysis and the capabilities to exploit opportunities effectively to realize their latent value. To help engineers and decision makers to reason in these terms, UVa is developing an approach and supporting tools to make opportunities, environments, and valuation techniques explicit and subject to scientific, value-driven management during system development.

3.2.2 Quantitative Evaluation of Flexibility Using a Case Study

UVa is still early in the development of its approach and supporting tools, and has not yet conducted in-depth case studies.

3.2.3 Strengths and Weaknesses

Strengths

- Emphasizes needs to convert theoretical work into science-based, practical tools for working engineers and decision-makers.
- Strongly recognizes that naïve application of real options theory is problematical, while retaining an overall perspective in terms of investment under uncertainty.
- Recognizing that there is still uncertainty about what valuation approaches will be best, creates opportunities to choose later through provision of a plug-in, i.e., modular, architecture.
- Intent is to provide several valuation techniques at the same time, including ones for valuing opportunities created by decision to delay investments, and by modular design architectures.

Weaknesses

- The usability of event trees with subjective probability estimates for modeling environments including uncertain future states of nature remains unclear.
- Continual updating of environment models as uncertain conditions resolve to certain outcomes could be burdensome.
- The provision of valid subjective estimates is difficult and subject to gaming.
- There are innumerable planned and unplanned opportunities in any project; picking the ones to model will pose challenges.
- Non-software engineers will not have ready access to the tools UVa is developing. UVa is exploring the use of Web 2.0 interfaces to supplement the programming interfaces that will be provided by UVa's "Eclipse"-based prototypes.
- Most real options and related approaches assume risk-neutral decision makers implicitly or explicitly. This assumption need to be checked in a risk management sense.

3.3 Knowledge Value Added + Integrated Risk Management and Real Options

3.3.1 Overview of the Approach

KVA+IRM analysis is designed to support technology portfolio acquisitions and to empower decision-makers by providing performance-based data and scenario analysis. With historical data provided by KVA, potential strategic investments can then be evaluated with Integrated Risk Management Analysis.

The KVA+IRM valuation framework measures operating performance, cost-effectiveness, return on investments, risk, real options (capturing strategic flexibility), and analytical portfolio optimization. The framework's components of data collection, KVA methodology, and Integrated Risk Management analysis collectively provide performance-based data and analyses on individual projects, programs and processes within a portfolio of IT investments.

KVA METHODOLOGY		REAL OPTIONS THEORY
Step 1: Calculate Time to Learn. **Step 2: Calculate Value of Output (K) for each sub-process.** **Step 3: Calculate Total K for process.** **Step 4: Derive Proxy Revenue Stream.** **Step 5: Develop the Value Equation Numerator by assigning revenue streams to sub-processes.** **Step 6: Develop value equation denominator by assigning costs to sub-processes.** **Step 7: Calculate metrics:** *Return on Investment (ROI)* *Return on Knowledge Assets (ROK)*	+	**Step 1: Risk Identification** List of projects and strategies to evaluate. **Step 2: Risk Prediction** Base case projections for each project. **Step 3: Risk Modeling** Develop static financial models with KVA data. **Step 4: Risk Analysis** Dynamic Monte Carlo simulation. **Step 5: Risk Mitigation** Framing real options. **Step 6: Risk Hedging** Options analytics, simulation & optimization. **Step 7: Risk Diversification** Portfolio optimization and asset allocation. **Step 8: Risk Management** Reports presentation and update analysis.

Figure 11: KVA+IRM NPS Valuation Framework

The KVA+RO valuation framework measures operating performance, cost-effectiveness and return on investments. Its methodology can be summarized in the following table including the general data collection process.

DATA COLLECTION	KVA METHODOLOGY	REAL OPTIONS THEORY
• Collect baseline data • Identify sub-processes • Research market comparable data • Conduct market analysis • Determine key metrics	**Step 1:** Calculate Time to Learn. **Step 2:** Calculate Value of Output (K) for each sub-process. **Step 3:** Calculate Total K for process. **Step 4:** Derive Proxy Revenue Stream. **Step 5:** Develop the Value Equation Numerator by assigning revenue streams to sub-processes. **Step 6:** Develop value equation denominator by assigning costs to sub-processes. **Step 7, 8, 9:** Calculate metrics: *Return on Investment (ROI)* *Return on Knowledge Assets (ROKA)* *Return on Knowledge Investment (RKOI)*	**Step 1: Risk Identification** List of projects and strategies to evaluate. **Step 2: Risk Prediction** Base case projections for each project. **Step 3: Risk Modeling** Develop static financial models with KVA data. **Step 4: Risk Analysis** Dynamic Monte Carlo simulation. **Step 5: Risk Mitigation** Framing real options. **Step 6: Risk Hedging** Options analytics, simulation & optimization. **Step 7: Risk Diversification** Portfolio optimization and asset allocation. **Step 8: Risk Management** Reports presentation and update analysis.

Figure 12: KVA+RO NPS Valuation Framework

Knowledge Value Added Methodology

A new paradigm in sub-corporate performance analytics, KVA measures the value provided by human capital assets and IT assets by analyzing an organization, process or function at the process-level. It provides insights into each dollar of IT investment by monetizing the outputs of all assets, including intangible knowledge assets. By capturing the value of knowledge embedded in an organization's core processes, employees and IT, KVA identifies the actual cost and revenue of a product or service. Because KVA identifies every process required to produce an output and the historical costs of those processes, unit costs and unit prices of products and services are calculated. An output is defined as the end result of an organization's operations; it can be a product or service as shown in the diagram below.

As a performance tool, the methodology:

Compares all processes in terms of relative productivity

Allocates revenues to common units of output

Measures value added by IT by the outputs it produces

Relates outputs to cost of producing those outputs in common units

Provides common unit measures for organizational productivity

Based on the tenets of complexity theory, KVA assumes that humans and technology in organizations add value by taking inputs and changing them into outputs through core processes [Housel and Bell 2001]. The amount of change an asset or process produces can be a measure of value or benefit. Additional assumptions include:

- Describing all process outputs in common units (i.e., the time it takes to learn to produce the required outputs) allows historical revenue and cost data to be assigned to those processes at any given point in time.
- All outputs can be described in terms of the time required to learn how to produce them.
- Learning Time, a surrogate for the knowledge required to produce process outputs, is measured in common units of time. Consequently, Units of Learning Time = Common Units of Output (**K**).

- Common unit of output makes it possible to compare all outputs in terms of cost per unit as well as price per unit, because revenue can now be assigned at the sub-organizational level.

- Once cost and revenue streams have been assigned to sub-organizational outputs, normal accounting and financial performance and profitability metrics can be applied.

Describing processes in common units also permits market comparable data to be generated, particularly important for non-profit organizations such as the DoD. Market comparable data from the commercial sector can be used to estimate price per common unit, allowing for revenue estimates of process outputs for non-profits. This also provides a common units basis to define benefit streams regardless of process analyzed KVA differs from other ROI models because it allows for revenue estimates enabling useof traditional accounting, financial performance and profitability measures and prospective financial methods as real options analysis.

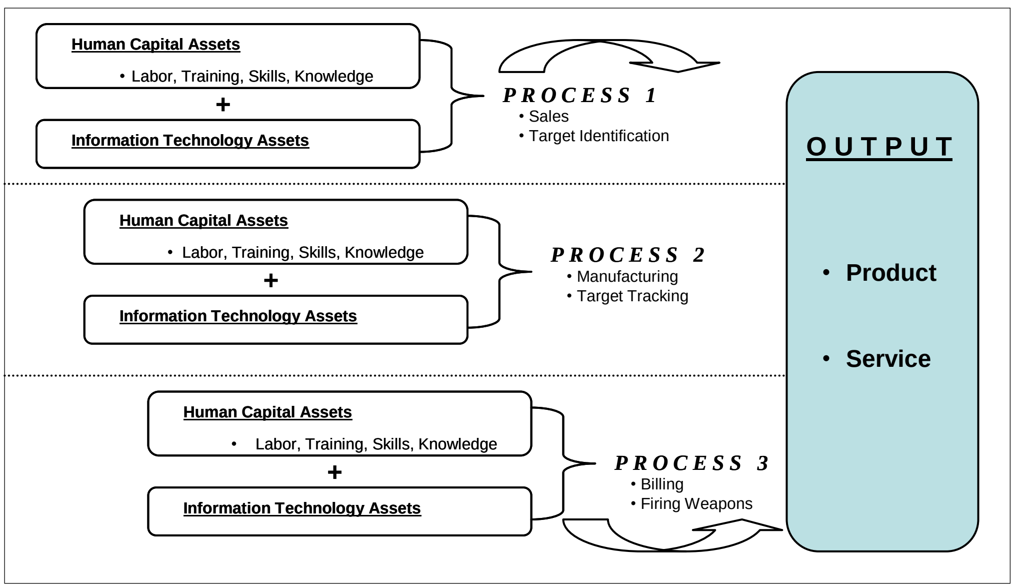


Figure 13: Measuring Output

Traditional Accounting/ Finance Measure	KVA Process Value Measure
Sales / Revenues	Common units of output
Product price	Market comparables: Price per unit of output
Total Revenues	Total units of output X price per unit = total revenue surrogate

Table 4: Comparison of Outputs

Traditional Accounting Benefits (Revenues) versus Process Based Value

KVA can rank processes in terms of the degree to which they add value to the organization or its processes. This assists decision-makers to identify what processes are value-added — those that will most likely accomplish a mission, deliver a service, or meet customer demand. Value is quantified in two(IRM)/four(RO) key metrics: Return-on-Knowledge (ROK) for KVA+IRM/RO, Return on Knowledge Assets (ROKA) for KVA+RO, Return on Knowledge Investment (ROKI) for KVA+RO and Return on Investment (ROI) for KVA+IRM/RO.

KVA analysis can be conducted through the three methods shown in the table below.

Steps	Learning Time	Process Description	Binary Query Method
1		Identify core process and its subprocesses.	
2	Establish common units to measure learning time	Describe products in terms of instructions required to reproduce them, and select unit of process description.	Create set of binary yes/no questions such that all possible outputs are represented as sequence of yes/no answers.
3	Calculate learning time to execute each subprocess.	Calculate number of process instructions pertaining to each subprocess.	Calculate length of sequence of yes/no answers for each subprocess.
4		Designate sampling period long enough to capture representative sample of core process's final product/service output.	
5	Multiply learning time for each subprocess by number of times subprocess executes during sample period.	Multiply number of process instructions used to describe each subprocess by number of times subprocess executes during sample period.	Multiply length of yes/no string for each subprocess by number of times this subprocess executes during sample period.
6		Allocate revenue to subprocesses in proportion to quantities generated by Step 5, and calculate costs for each subprocess.	
7		Calculate ROK, ROI, and interpret results.	

Table 5: Approaches to KVA Calculation (Source: Housel & Bell, 2001)

Real Options Analysis

Real Options analysis, also a step in the IRM approach, incorporates strategic planning and analysis, risk assessment and management, and investment analysis. As a financial valuation tool, Real Options allow organizations to adapt decisions to respond to unexpected environmental or market developments. As a strategic management tool, Real Options are a strategic investment valuation tool affording decision-makers the ability to leverage uncertainty and limit risk.
The value of information is clear after the uncertainty is resolved. This value of information is called as the ex-post value of information. The ex-post value of information is just the difference between the value of decisions with and without the information, and it can be expressed as following equation;

$$VOI = V(x^I) - V(x^0)$$

where, VOI and V stands for the value of information and the value of decision, respectively. $x$denotes the decision variable. $x^I$is the best choice of the decision maker given the information and x^0 stands for the best choice without the information, i.e.,

$$x^I = \arg\max_x \mathbb{E}[V(x)|I]$$
$$x^0 = \arg\max_x \mathbb{E}[V(x)]$$

where$\mathbb{E}[\cdot]$ means expected value.

When the information is perfect, the expected value of the information can be calculated as following. Let i and j denote the choice and future status, respectively. $p_j$means the probability that the status j occurs. R_{ij}stands for the pay off that the decision maker chooses the action i and status j happens. Then the expected value of the perfect information (EVPI) is

$$EVPI = \sum_j p_j(\max_i R_{ij}) - \max_i \sum_j p_j R_{ij}$$

An example can help to understand the mathematical model of the value of information. Following table shows the possible future economic status; boom and depression, feasible investment instruments; stock and bond, and payoffs according to the status and instruments.

	Stock	*Bond*
Boom	20	2
Depression	-10	2

Suppose that the decision maker has the information that the probability of boom is 50% and the probability of depression is 50%. Then the expected value of stock is 5 and the expected value of bond is 2. Therefore investing to stock is chosen ($x^0 = stock$). Consider the decision maker obtains the information that the probability of boom is 0 and that of depression is 1. When the decision maker uses this information, he should choose bond ($x^I = bond$). If the real future situation is depression, the value of this information is $V(x^I) - V(x^0) = 2 - (-10) = 12$. On the other hand, if the future situation is boom, the value of this information is $2 - 20 = -18$. Due to the wrong information, the decision maker makes an undesirable decision. So the value of the information is negative.

When there exists the perfect information about future status, we can calculate the expected value of the perfect information. Note that once the perfect information is acquired, we know the future status for sure. However before we have the information we don't know what it will tell us. If the perfect information tells that future status is boom, investing to stock should be chosen. Otherwise, the decision should be bond. What is the probability that the perfect information tells that the future status is boom or depression? The only available information is the current information. Therefore, the value of perfect information is

$$EVPI = (0.5 \times 20 + 0.5 \times 2) - (0.5 \times 20 + 0.5 \times -10) = 11$$

According to Hirshleifer and Riley [1979], the value of information is an outcome of choice in uncertain situations. The general conclusions from models of information are that its value largely depends on several factors:

- How much flexibility decision makers have
- The value of output in the market
- The cost of the information
- What is the opportunity cost of the information

The first factor means that the information is more valuable as the feasible actions are various. Although a decision maker has very accurate information, if he has no choice but doing as he has done, the information is useless. The second factor implies that the value of information is derived from the demand of the ultimate output. For example, the value of information about the deposit of oil depends on the price of oil. If the price of oil is zero, the value of information is also zero, no matter how the information is accurate.

3.3.2 QUANTITATIVE EVALUATION OF FLEXIBILITY USING CASE STUDIES

SHIPMAIN: The Knowledge Value Added + Integrated Risk Management (KVA+IRM) framework is used to quantify process improvements and the potential benefits of select technology on the ship maintenance and modernization (SHIPMAIN) program.

SHIPMAIN is a large program with many interrelated concepts, instructions, policies, and areas of study.

SHIPMAIN is one of the latest initiatives aimed at garnering efficient ways to get the job done. It is a best business practice that fleet sailors and shipyards are utilizing to change the culture of completing ship work. The Navy implemented the SHIPMAIN process in FY 2004 to:

- Increase efficiency of maintenance and modernization process without compromising effectiveness,
- Define common planning process for surface ship maintenance and alterations,
- Install disciplined management process with objective measurements, and
- Institutionalize that process and provide continuous improvement methodology for it. (Commander, Naval Sea Systems Command, 2006)

SHIPMAIN is about doing the right maintenance at the right time, in the right place for the right cost. The initiative seeks to identify redundancies in maintenance processes and eliminate them. It provides a single process, assisting the Navy in realizing the maximum benefit per maintenance dollar by eliminating time lags, prioritizing ship jobs and empowering Sailors in their maintenance decisions (Commander, Naval Sea Systems Command, 2006).

The SHIPMAIN process is comprised of five distinct phases1 and three Decision Points (DP)2 to take a proposed change from concept to completion in one document: the Ship Change Document (SCD). (See Appendix for more details)

KVA Analysis: As-is Scenario: A summary of the high-level, As-is KVA analysis is depicted in Table 6. These estimates were compiled from interviews of SMEs at NAVSEA and from historical data contained in the NDE. This sample is representative of availability periods for ships of the Pacific and Atlantic Fleet, including Aircraft

[1]Five Phases: I-Conceptual, II-Preliminary Design, III-Detailed Design, IV-Implementation, V-Installation (Commander, Naval Sea Systems Command, 2006).
[2] DPs occur at the conclusion of Phases I-III. Each DP is an approval for funding of successive phases and has an associated Cost Benefit Analysis (CBA), Alteration Figure of Merit (AFOM) and Recommended Change Package (RCP) (Commander, Naval Sea Systems Command, 2006).

Carriers, averaged from FY 2002 to FY 2007. All estimates contained in this analysis are as conservative and accurate as possible.

KVA Results: To-be Scenario: The SHIPMAIN process was reengineered by adding 3D laser scanning tools and a comprehensive suite of PLM products to the as-is state. Implementation of 3D laser scanning tools will primarily affect Block 265.1 by enabling the planning yard to acquire images and output its drawings in a highly accurate and electronically transferable 3D format—as opposed to static installation drawings delivered on paper. The 3D scanning tools can produce a 2D output also, as currently required under the FMP. With the addition of a robust PLM product suite, the 3D images generated can be shared across the enterprise in an Integrated Data Environment, allowing all stakeholders real-time access to highly accurate as-built imagery through a single interface.

As Is SHIPMAIN Process Overview

Core Process	Process Title	Number of Employees	Total Benefits	Total Cost	ROK	ROI
Block 250	Authorize and Issue Letter of Authorization (LOA)/Hull Maintenance Plan (HMP); Generate 2Ks	9	$22,619,472	$5,311,299	426%	326%
Block 265	Hull Installation and Risk Assessment	44	$94,928,918	$130,071,059	73%	-27%
Block 270	Authorize Installation	4	$24,710,347	$3,161,555	782%	682%
Block 280	Resolve "Not Authorized/Deferred SC	1	$3,706,552	$619,523	598%	498%
Block 300	Install SC	46	$94,722,998	$40,617,720	233%	133%
Block 310	Feedback: Cost, CM, Performance, Schedule, ILS	2	$1,853,276	$619,523	299%	199%
Block 320	Continue Installs	5	$4,633,190	$3,068,367	151%	51%
Block 330	Final Install, Closeout SC	1	$926,638	$309,762	299%	199%
			$248,101,392	**$183,778,809**	**135%**	**35%**

Table 6: SHIPMAIN Phases IV and V As-is Core Process Model

Implementation of an enterprise-wide PLM product suite demonstrated a remarkable effect on each core process. Providing stakeholders access to real-time information related to all iterations of the product lifecycle in a collaborative environment enabled nearly all sub-processes to benefit. Processes that didn't demonstrate a quantitative improvement in this model will likely show qualitative improvements (which will be discussed in the Conclusions section). Table 7 depicts the change in cost and ROI factors from the As-is to the To-be scenario. The majority of the estimates contained in this table were derived from interviews with SMEs from NAVSEA and SIS and from a comprehensive review of the business rules listed in Appendix D of the SCEPM dated December 11, 2006.

Results shown in Table 7 demonstrate that overall costs would be reduced by nearly $78 million dollars, despite additional expenditures of acquiring 3D laser scanning and PLM tools. It is apparent that cost savings are achieved in all processes, with the exception of

Block 270, as a result of 3D laser scanning and PLM tools. As the technologies mature, and work processes are modified to maximize their potential, cost savings and ROI should continue to improve over time.

Core Process	Process Title	Annual As-Is Cost	Annual To-Be Cost	Difference (Cost Savings)	As-Is ROI	To-Be ROI
Block 250	Authorize and Issue Letter of Authorization (LOA)/Hull Maintenance Plan (HMP); Generate 2Ks	$5,311,248	$2,287,671	**$3,023,577**	326%	**565%**
Block 265	Hull Installation and Risk Assessment	$130,060,112	$63,437,554	**$66,622,558**	-27%	**155%**
Block 270	Authorize Installation	$3,161,600	$3,217,805	**($56,205)**	682%	**668%**
Block 280	Resolve "Not Authorized/Deferred SC	$619,424	$427,964	**$191,460**	498%	**766%**
Block 300	Install SC	$40,616,160	$33,433,420	**$7,182,740**	133%	**183%**
Block 310	Feedback: Cost, CM, Performance, Schedule, ILS	$619,424	$242,107	**$377,317**	199%	**665%**
Block 320	Continue Installs	$3,068,520	$2,510,944	**$557,576**	51%	**131%**
Block 330	Final Install, Closeout SC	$309,712	$304,059	**$5,653**	199%	**205%**
	Totals:	**$183,766,200**	**$105,861,524**	**$77,904,676**		

Table 7: As-is and To-be Cost and ROI Value Differences

KVA Real Options Analysis: Real Options analysis was performed to determine the prospective value of three basic options over a three-year period using KVA data as a platform. The Approach involves the following eight procedural steps:

1. Qualitative management screening
2. Forecasting and prediction
3. Base-case KVA net present value and ROI analysis
4. Risk-based Monte Carlo simulation
5. Strategic Real Options problem framing and courses of action
6. Real Options modeling and analysis
7. Analytical portfolio and resource optimization
8. Reporting and update analysis

After running the different scenarios, "To Be" and "Radical To Be" provide highest overall total strategic value with little difference between the two (19.51 to 20.49 times improvement over the baseline "As Is" option). However, when considering all the downstream options available from collaborative technologies with 3D scanning

capabilities, the "Radical To Be" course of action is the best, providing an overwhelming 68.88 times the returns from the existing "As Is" base case.

Maturity (Years)	5		
Risk-Free Rate (%)	5.00%		
Strategic Option Valuation			
	AS-IS	**TO-BE**	**RADICAL**
Benefits	$ 49,175,536.83	$ 93,344,192.00	$ 95,097,452.00
Costs	$ 44,705,033.48	$ 7,854,206.09	$ 4,488,887.70
Volatility	N/A	8.04%	9.81%
Total Strategic Value	$ 4,470,503.35	$ 87,227,330.00	$ 91,601,502.00
Factor Increase		19.51	20.49
Expansion Valuation on Stage-Gate Options			
Maturity (Years)	10	10	10
Factor Increase	3	3	10
	AS-IS	**TO-BE**	**RADICAL**
Benefits	$ 147,526,610.48	$ 280,032,576.00	$ 950,974,520.00
Costs	$ 134,115,100.43	$ 23,562,618.26	$ 44,888,876.96
Volatility	N/A	25.43%	31.02%
Long Term Total Strategic Value	$ 13,411,510.04	$ 265,742,275.00	$ 923,752,800.00
Factor Increase		19.81	68.88

Table 8: Summary of Results

The options analysis clearly indicated that real benefits of using the combined technologies is in the future value they will create over time. While the cost savings from the use of these technologies is substantial, the real story is in the future value these options will create through greater flexibility in including many vendors in the bidding process, a reduced cycle time in completing the maintenance, and the possibility of creating "portless" maintenance for ships while at sea or in foreign ports.

CCOPS: KVA methodology was applied to quantify the value added by Cryptologic Carry-On Program (CCOP) systems, information warfare/cryptologic operators, and the enabling ship borne system infrastructure with which they interact. Value provided by human capital elements were compared to IT elements to measure efficiency (productivity) and effectiveness (profitability). All assets, sub-processes, and outputs are first identified.

- ***Asset*** analysis encompasses all value and cost data related to each asset in the process, human capital or IT asset.
- ***Sub-process*** analysis includes a detailed breakdown of the ICP to include the time-to-learn, how to perform each sub-process, and number of executions for each sub-process.

- ***Process*** outputs are established via time to learn estimates, including the total number of aggregated process outputs and a surrogate revenue stream used to monetize the outputs.

Asset values and costs are then allocated throughout the sub-processes in which they contribute to the production of outputs. The time-to-learn (knowledge embedded in each sub-process) is multiplied by the number of executions of that sub-process, and the figure serves as a basis for revenue allocation at the sub-process level. Costs are calculated by multiplying the time it takes to produce the process output times the salary of those producing it and the cost per usage of the IT asset. Costing typically does not include the cost of fixed assets as these costs are typically used as a constant weighting factor. Therefore, these costs usually do not affect the relative performance estimates for the various sub-processes. Performance ratios such as ROKA and ROKI can be calculated after costs and benefits for each sub-process are defined. (See Appendix for more details)

KVA Results: KVA analysis was used to compare two example sub-processes: "Search and Collect" (P4) and "Format Data for Report Generation" (P8). Results are summarized in the following tables and issues were identified at the portfolio, program and process levels.

Sub-Process		CCOP A	CCOP B	CCOP C	CCOP D	ROK
Review Request/Tasking	P1	168.54%				168.54%
Determine Op/Equip Mix	P2	166.86%				166.86%
Input Search Function/CoveragePlan	P3	152.91%				152.91%
Search/Collection Process	P4	930.03%	148.15%			590.13%
Target Data Acquisition/Capture	P5	290.15%	147.71%			228.23%
Target Data Processing	P6	319.39%	162.59%	436.13%	28.18%	142.41%
Target Data Analysis	P7	149.98%		534.76%	34.55%	121.42%
Format Data for Report Generation	P8	143.34%				143.34%
QC Report	P9	315.88%				315.88%
Transmit Report	P10	148.75%				148.75%
ROK for Total Process		278.59%	152.81%	485.44%	31.37%	196.27%

Table 9: Return on Knowledge (ROK) USS READINESS Summary KVA Results

CCOP D is a cost-heavy system that executes very few times with negative ROKs throughout the sample period, as seen in Table 9.

- Is CCOP D appropriate for this platform and mission?
- What is a less expensive alternative to CCOP D?
- Are all operators appropriately trained in the use of CCOP D?

Sub-Process		**CCOP A**	**CCOP B**	**CCOP C**	**CCOP D**	**ROKI**
Review Request/Tasking	P1	68.54				22.11
Determine Op/Equip Mix	P2	66.86				20.89
Input Search Function/Coverage Plan	P3	52.91				-18.44
Search/Collection Process	P4	830.03	48.15			*239.01*
Target Data Acquisition/Capture	P5	190.15	47.71			47.28
Target Data Processing	P6	219.39	62.59	336.13	-71.82	36.67
Target Data Analysis	P7	49.98		434.76	-65.45	21.25
Format Data for Report Generation	P8	43.34				*-20.37*
QC Report	P9	215.88				79.19
Transmit Report	P10	48.75				-17.37
Metrics for Aggregated		178.59	52.81	385.44	68.63	109.9

Table 10: Return on Knowledge Investment (ROKI) USS READINESS Summary KVA Results

The Search and Collect process (P4) is knowledge-intensive requiring IT and human capital asset investments to complete, as indicated in Table 10. Moreover, each process output necessitates many executions of the sub-process.

- Could an even higher return be achieved with further automated search and collection systems or more operators?

- Should the amount of knowledge in humans and IT be adjusted?
- Could a broader range of training allow operators to perform more functions?

The Search and Collect process (P4) is a high performer with an overall return of 239% compared to a -20.37% return for the Format Data for Report Generation process (P 8).

- What accounts for the discrepancy in the returns received on each process?

The Format Data for Report Generation process (P 8) only executes once per intelligence report (process output) with nearly one third of all operators assigned to this sub-process one fifth of the total human cost.

- What causes this low efficiency level?

The Format Data for Report Generation process (P 8) is more automated than P4.

- Could this process be further automated or performed by other operators to yield higher efficiency **and** effectiveness levels?

Real Options Analysis: Real options analysis was performed to determine the prospective value of three basic options over a three-year period using KVA data as input for the analysts. Three potential scenarios were identified.

Option A Remote to Shore	Option B Direct Support	Option C Permanent SSES
• Data viewed from geographically remote center. • Intelligence collection processing from consolidated center requires less intelligence personnel on ships. • Consolidating capabilities into central center popular movement to cut costs and provide more shore based operations to support war-fighting capabilities. • Similar to consolidation of service operations in businesses into larger and fewer call centers.	• CCOP equipment & operators move from ship to ship whenever a ship came into port for maintenance, repair or modernization. • Fewer sets of CCOP equipment and operators required to service intelligence gathering needs of the fleet.	• CCOP systems and operators assigned to given ships at all times. • Requires more operators and CCOP systems. • Potential costs increases, provides more control of intelligence capability by the ships and fleet commanders.

Table 11: CCOP Strategic Scenarios

Each strategic scenario is explored further.

Results of the real options analysis indicate that Option C delivers the highest value at $15.2 million. Although apriori, Options A and B were expected to have significant cost savings, it is possible to see greater total value, with much lower volatility (risk), for Option C with RO analysis. Fleet and Ship Commanders who intuitively preferred Option C because it permitted greater control of intelligence assets for specific operations, now have objective data to help them review their preferred option. This is

not to say that the other options might provide greater strategic value in the long run once they are implemented with more productive CCOPs assets and lower volatility based on overcoming the initial decrements in the learning curve of a new process implementation.

	Option A	Option B	Option C
PV Option Cost (Year 1)	$348,533	$1,595,697	$1,613,029
PV Option Cost (Year 2)	$4,224,487	$3,043,358	$4,494,950
PV Option Cost (Year 3)	$3,688,994	$10,105,987	$8,806,643
PV Revenues	$24,416,017	$33,909,554	$38,820,096
PV Operating Costs	$16,220,188	$16,765,513	$9,951,833
PV Net Benefit	**$8,195,829**	**$17,144,041**	**$28,868,264**
PV Cost to Purchase Option	$425,000	$169,426	$72,611
Maturity Years	3.00	3.00	3.00
Average Risk-Free Rate	3.54%	3.54%	3.54%
Dividend Opportunity Cost	0.00%	0.00%	0.00%
Volatility	26.49%	29.44%	15.04%
Total Strategic Value with Options	**$1,386,355**	**$4,466,540**	**$15,231,813**

Table 12: Summary Real Options Analysis Results

3.3.3 Strengths and Weaknesses

Strengths

- Quantifies value of specific processes, functions, departments, divisions, or organizations in common units of output.
- Provides historical data on costs and revenues of specific processes and specific programs within organizations.
- Provides a methodology that will facilitate regulatory compliance in the public sector with legislation such as the Clinger-Cohen Act of 1996 mandating portfolio management for all federal agencies. In the private sector, it can facilitate compliance with Sarbanes-Oxley by making performance among corporate entities more transparent.
- Highlights operational efficiencies/inefficiencies at any level of analysis, down to individual employees and IT system.
- Leverages current and future portfolio investments by estimating the potential total value created.

Weaknesses

- Financial options' assumptions, such as no arbitrage condition, complete market condition and infinite liquidity, may not hold for the non-financial market.
- Without checking the assumption of Black-Scholes model, using the Black-Scholes formula does not make sense. For example, the strongest assumption of the model is the fact that uncertainty can be modeled in geometric Brownian motion and as a result the distribution of future status is log-normal distribution. If the future environment cannot be modeled with this stochastic process and distribution, the Black-Scholes model is not valid.
- In the real world decision, there are many qualitative characteristics to be considered. In the real option approach it is hard to be considered.
- Almost all real options related literature assumes the risk-neutral decision maker implicitly or explicitly. This assumption need to be check in risk management sense.
- With the raw data required for the analysis residing in multiple databases of varying classification levels, data-gathering mechanisms that are less human-intensive and more automated need to be created to extract the required information.
- Although the ICP in this case study was developed through the use of subject matter experts, a standard description and definition of each sub-process should be reached through an Intelligence Community-wide consensus of process stake-holders.
- A more detailed research should be conducted to analyze the knowledge embedded in each IT system to accurately capture the benefits resulting from the execution of particular system processes.
- The Market Comparables approach to valuing the outputs of non-profit organizations, although used as a rough baseline to monetize outputs in this case study, requires a more in-depth look at comparable organizations utilizing similar processes to produce similar outputs. The creation of a broad database of such organizations is currently being conducted to benchmark industries by functional groupings and products.
- To provide a more powerful analysis of the ICP, a database of comparable historical KVA information should be created to benchmark future work or to provide a broader insight for current work.

4 RESEARCH ROADMAP

4.1 Gap Analysis

In our gap analysis, we address challenges in applying the MPTs above, and also do a top-level exploration of the case involving different sources of change. Example challenges include foreseeable but uncontrollable sources of change, such as with externally evolving interoperating systems, and modularizing around multiple sources of change. For example, adding a new data input will require coordinated changes among the data management module, data-entry user interface module, and mission logic module. It is also the case that unforeseeable changes may not be confined to a single module. Then one will often have architecture-breakers and need alternative approaches. For this situation, no good theoretical basis is available, and projects can at best put together various individual strategies to better accommodate unforeseeable change. These strategies include trend analysis and autonomy; user programmability; value-based, lean, and agile methods; and evolutionary acquisition with concurrent architecture rebaselining.

The gap analysis also identifies the major risks associated with MPTs for both achievement and valuation of flexibility, primarily for the foreseeable-change case, but also considering the unforeseeable change case. These risks include difficulties in achieving scalability, generality, usability, and adversary-proofing of the flexibility MPTs, and the risk of overemphasizing flexibility and creating unacceptable tradeoffs with other KPPs. They will be mitigated where possible by comparison of alternative valuation methods, but primarily addressed by the gap analysis and creation of a research roadmap for addressing them at higher levels of scale, realism, and adversary-based evaluation.

Real options have garnered much attention among researchers interested in extending the analytical results and computational methods associated with financial options to areas of application well outside the field of Finance. There is now a large literature devoted the theory and deployment of so real options reporting theory and practice. Nonetheless, there remain many open questions regarding the appropriate use of of real option theory in practice. We wish to review some of the cautionary considerations regarding the application of real option theory in the context of military procurement processes and the valuation of flexibility. To this end, we appeal to summary concerns reported in the open literature de Neufville (2002), Hubalek and Schachermayer, (1999), Wang and de Neufville (2005) together with our own observations.

- Real options must be described in terms of specific technologies and the systemic domain in which they are to be developed. Financial analysis alone is insufficient

to frame real options. This is quite difficult, when as yet undeveloped technologies are under consideration.

- Financial options are well-defined contracts that are tradable and individually valued, while real options are not.: real options have no contract-specified exercise price of time. The usefulness of valuing every potential program alternative that provides flexibility is not clear.
- In military procurement programs, previous experiences associated with the development of similar technologies are not necessarily available. Hence, valuing real options on the basis of so called "comparables" becomes questionable because of the absence of available data
- Real options are most often path-dependent. Hence, direct applicability of traditional financial options methodologies is not appropriate, as the underlying stochastic differential equations are not necessarily available
- Real options in military acquisition programs are likely to be highly interdependent. Traditional financial option pricing methods fail here, again, because underlying stochastic differential equations may be unattainable.
- In military procurement programs, there may be no justifiable reason to accept the "no arbitrage assumption". In this case, general option pricing theory breaks down.
- There is typically no quantitative or qualitative reason to believe the real options have uncertainty in price that follow Brownian motion. That is, unlike in financial markets where there exist both quantitative and qualitative analyses that support by weak convergence in measure principles that suggests a limiting Brownian motion price process, there is typically no similar reasoning supporting the assumption of Brownian behavior. Hence, the semi-martingale arguments leading to the principal results of general option pricing are not applicable.

Effect of Errors in Uncertainty Estimation: What happens if a decision maker's estimation about future uncertainty is wrong? What is the damage of abusing Black-Scholes model? Maximum entropy principle provides an important implication to these questions. The probability distribution that best describes the current information is the distribution maximizing the information entropy. In other words, when we have testable information, the true probability distribution with respect to the current information maximizes the entropy. The principle was first illustrated by E.T Jaynes in 1957.
For a discrete random variable with distribution

$$\mathbb{P}(X = x_k) = p_k, \qquad for\ k = 1,2,\cdots$$

the entropy of X is defined as

$$H(X) = -\sum_k p_k \log p_k$$

For a continuous random variable X with probability density function $p(x)$, the entropy of X is defined as

$$H(X) = -\int_{-\infty}^{\infty} p(x) \log \frac{p(x)}{m(x)} dx$$

Where,$m(x)$ is called invariant measure.

The testable information is the statement of current information to determine whether or not a given distribution is consistent with it. The testable information plays a role of constraints of the maximization problem. For discrete case, maximum entropy probability distribution is derived with following procedure. Let I be testable information about a quantity x which takes values in $\{x_1, x_2, \cdots, x_n\}$. Suppose that we have m testable information of the distribution which is represented as

$$\sum_{i=1}^{n} \mathbb{P}(x_i|I) f_k(x_i) = F_k, \qquad k = 1, \cdots, m$$

Moreover, the sum of probabilities should be 1. Therefore

$$\sum_{i=1}^{n} \mathbb{P}(x_i|I\ ) = 1$$

With these constraints, the probability distribution with maximum information entropy is

$$\mathbb{P}(x_i|I) = \frac{1}{Z(\lambda_1, \cdots, \lambda_m)} \exp[\lambda_1 f_1(x_i) + \cdots + \lambda_m f_m(x_i)]$$

Where, $Z(\lambda_1, \cdots, \lambda_m) = \sum_{i=1}^{n} \exp[\lambda_1 f_1(x_i) + \cdots + \lambda_m f_m(x_i)]$ and the parameters λ_k determined by the constraints $F_k = \frac{\partial}{\partial \lambda_k} \log Z(\lambda_1, \cdots, \lambda_m)$.

For continuous distribution, some testable information, I, about x takes values in a interval $[a, b]$. This information is expressed in constraints on the expectations of the function f_k.

$$\int_{a}^{b} p(x|I) f_k(x) dx \ = F_k, \qquad k = 1, \cdots, m$$

The obvious constraint is given by

$$\int_{-\infty}^{\infty} p(x|I) dx = 1$$

The probability distribution that maximize the entropy of $p(x)$ subject to the constraints is

$$\mathbb{P}(x_i|I) = \frac{1}{Z(\lambda_1, \cdots, \lambda_m)} m(x) \exp[\lambda_1 f_1(x_i) + \cdots + \lambda_m f_m(x_i)]$$

Where $Z(\lambda_1, \cdots, \lambda_m) = \int m(x) \exp[\lambda_1 f_1(x_i) + \cdots + \lambda_m f_m(x_i)]\, dx$. Similar to the discrete case, the coefficients $\lambda_1, \cdots, \lambda_m$ are determined by the constraints

$$F_k = \frac{\partial}{\partial \lambda_k} \log Z(\lambda_1, \cdots, \lambda_m)$$

Example

Suppose that a random variable x takes a value from $\{0,1,2,\cdots,100\}$. A decision maker is considering to implement a flexible system that makes it possible to choose system A, B or C according to the realization of x. The payoff of system $A$is $A = -x + 30$. The system B pays $B = -(x - 30)(x - 70)$. The $C = x - 70$ represents the payoff of the system C. Figure 14 shows the payoff of each system

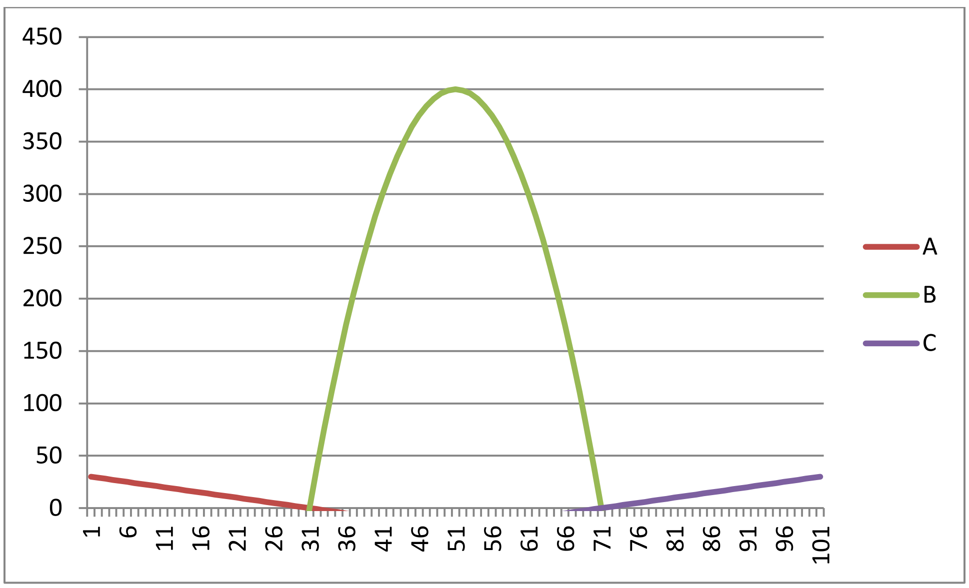


Figure 14 Payoffs of systems

Let $V^*(x)$ be the value of optimal choice when the future state is x. Then $V^*(x)$ can be expressed as

$$V^*(x) = \begin{cases} -x + 30 & 0 \le x < 30 \\ -(x - 30)(x - 70) & 30 \le x < 70 \\ x - 70 & 70 \le x \end{cases}$$

What is the value of this flexible system? The value of the system depends on the future uncertainty. We can express the expected value of the system as

$$\sum_{i=0}^{100} \mathbb{P}(x = i) \cdot V^*(i)$$

Suppose that we have the information that in the future $\mathbb{P}(x \leq 30) = 0.1$, $\mathbb{P}(x \leq 50) = 0.4$ and $\mathbb{P}(x \leq 80) = 0.8$.

Binomial distribution assumption: If the decision maker assumes that the random variable x follows binomial distribution, the distribution parameters can be estimated with least square method as follows.

$$\min_p [\{F_{bi}(30; 100, p) - 0.1\}^2 + \{F_{bi}(50; 100, p) - 0.4\}^2 + \{F_{bi}(80; 100, p) - 0.8\}^2]$$

where, $F_{bi}(k; n, p)$ stands for the cumulative distribution of binomial distribution up to k with parameters n and p, i.e., $F_{bi}(k; n, p) = \sum_{x=0}^{k} \binom{n}{x} p^x (1-p)^{n-x}$.

The estimation result is $p^* = 0.5176$. The expected value of the flexible system under the binomial distribution assumption is

$$\sum_{x=0}^{100} \binom{100}{x} 0.5176^x (0.4824)^{100-x} \cdot V^*(x) = 371.94$$

Geometric distribution assumption: The decision maker may assume that the random variable x follows exponential distribution, since x takes positive integer value. With the similar estimation procedure of binomial distribution case,

$$\min_p [\{F_{ex}(30; p) - 0.1\}^2 + \{F_{ex}(50; p) - 0.4\}^2 + \{F_{ex}(80; p) - 0.8\}^2]$$

where, $F_{ex}(k; p) = 1 - (1-p)^{k+1}$ stands for the cumulative distribution of exponential distribution. The estimation result $p^* = 0.0117$. The expected value of the flexible system under the geometric distribution assumption is

$$\sum_{x=0}^{100} 0.0117 \times 0.9883^x \cdot V^*(x) = 86.24$$

Maximum Entropy probability distribution: The testable information can be rewritten as following constraints.

$$\sum_{i=0}^{100} \mathbb{P}(x=i)\cdot \mathbb{I}_{x\le 30} = 0.1$$

$$\sum_{i=0}^{100} \mathbb{P}(x=i)\cdot \mathbb{I}_{x\le 50} = 0.4$$

$$\sum_{i=0}^{100} \mathbb{P}(x=i)\cdot \mathbb{I}_{x\le 80} = 0.8$$

We can invert these constraints to followings for convenience of calculation.

$$\sum_{i=0}^{100} \mathbb{P}(x=i)\cdot \mathbb{I}_{x\le 30} = 0.1$$

$$\sum_{i=0}^{100} \mathbb{P}(x=i)\cdot \mathbb{I}_{31\le x\le 50} = 0.3$$

$$\sum_{i=0}^{100} \mathbb{P}(x=i)\cdot \mathbb{I}_{51\le x\le 80} = 0.4$$

$$\sum_{i=0}^{100} \mathbb{P}(x=i) = 1$$

$\therefore f_1(x_i) = \mathbb{I}_{x_i\le 30}$, $F_1 = 0.1$, $f_2(x_i) = \mathbb{I}_{31\le x\le 50}$, $F_2 = 0.3$,$f_3(x_i) = \mathbb{I}_{51\le x\le 80}$, $F_3 = 0.4$, $f_4(x_i) = 1$ and $F_4 = 1$,where $\mathbb{I}$ represents the indicator function. The maximum entropy function with these constraints are known as a piecewise uniform distribution.

$$Z(\lambda_1,\lambda_2,\lambda_3,\lambda_4) = 31\exp[\lambda_1+\lambda_4] + 20\exp[\lambda_2+\lambda_4] + 30\exp[\lambda_3+\lambda_4] + 20\mathrm{exp}\,[\lambda_4]$$

$$\frac{\partial}{\partial\lambda_1} Z(\lambda_1,\lambda_2,\lambda_3,\lambda_4) = \frac{1}{Z(\lambda_1,\lambda_2,\lambda_3,\lambda_4)} 31\exp[\lambda_1+\lambda_4] = 0.1$$

$$\frac{\partial}{\partial\lambda_2} Z(\lambda_1,\lambda_2,\lambda_3,\lambda_4) = \frac{1}{Z(\lambda_1,\lambda_2,\lambda_3,\lambda_4)} 20\exp[\lambda_2+\lambda_4] = 0.3$$

$$\frac{\partial}{\partial \lambda_1} Z(\lambda_1, \lambda_2, \lambda_3, \lambda_4) = \frac{1}{Z(\lambda_1, \lambda_2, \lambda_3, \lambda_4)} 30 \exp[\lambda_3 + \lambda_4] = 0.4$$

$$\frac{\partial}{\partial \lambda_1} Z(\lambda_1, \lambda_2, \lambda_3, \lambda_4) = \frac{1}{Z(\lambda_1, \lambda_2, \lambda_3, \lambda_4)} 20 \exp[\lambda_4] = 1$$

$$\therefore \exp(\lambda_4) = \frac{1}{20} Z(\lambda_1, \lambda_2, \lambda_3, \lambda_4)$$

$$\exp(\lambda_1) = \frac{2}{31}$$

$$\exp(\lambda_2) = 0.3$$

$$\exp(\lambda_3) = \frac{8}{30}$$

$$\mathbb{P}(x = 0) = \frac{1}{Z(\lambda_1, \lambda_2, \lambda_3, \lambda_4)} \exp[\lambda_1 + \lambda_4] = \frac{1}{Z(\lambda_1, \lambda_2, \lambda_3, \lambda_4)} \exp[\lambda_1] \exp[\lambda_4]$$

$$= \frac{1}{Z(\lambda_1, \lambda_2, \lambda_3, \lambda_4)} \exp[\lambda_1] \frac{1}{20} Z(\lambda_1, \lambda_2, \lambda_3, \lambda_4) = \frac{1}{20} \cdot \frac{2}{31} = \frac{0.1}{31}$$

The maximum information entropy distribution, which is sometimes called the Gibbs distribution, is piecewise uniform distribution as following

$$p(x) = \begin{cases} \frac{0.1}{31} & x = 0, 1, \cdots 30 \\ \frac{0.3}{20} & x = 31, 32, \cdots, 50 \\ \frac{0.4}{30} & x = 51, 52, \cdots, 80 \\ \frac{0.2}{20} & x = 81, 82, \cdots, 100 \end{cases}$$

$$\therefore \sum_{x=0}^{100} p(x) \cdot V^*(x) = 157.68$$

In summary, according to the assumption of the future uncertainty, the evaluation of flexibility can be different. As this simple example shows, under the binomial assumption, the value of flexibility is overestimated about two times. On the other hand,

under the geometric distribution assumption, a decision maker may underestimate the value of flexibility only half of its value.

We are currently working on developing a test bed based on these principles using a defense satellite domain case study.

4.2 Developing a Framework for Valuing Flexibility

Considering the current state-of-the-art and the gaps found in the current capabilities to value flexibility, we are working towards developing an analytically rigorous framework for defining and valuing flexibility that adheres to the mathematical foundations of characterizing uncertainty and fundamental tenets of rational decision making under uncertainty.

A candidate value-based definition of flexibility is, "A system is flexible to the extent that it can be cost-effectively modified to meet new needs or to capitalize on new opportunities."

In this context, "Cost" includes dollars, calendar time, critical skills, and other scarce resources (facilities, equipment, supplies, etc.). It also includes the costs of flexibility-induced decrements in other system attributes (performance, security, safety, usability, etc.)."Effectiveness" includes improvements in military outcomes across a range of weighted scenarios, and cost avoidance (e.g., cost of delay).

Some implications of this definition are that the value of flexibility, V(F), will vary by mission and by range of scenarios. Thus, there is no one-size-fits-all, silver bullet V(F) formula. Also, V(F) will vary by its impact on other system attributes. Examples of flexibility-induced decrements are:

- With performance: loose vs. close coupling (supercomputing)
- With development cost and schedule: more to design, develop, V&V (rapid fielding)
- With maintainability: more side effects to address (automotive)
- With usability: too many options (Office 2007, TV-DVD-VCR wand)
- With security: too many entry points (Windows)

The following discussion provides our initial work on formalizing the value based notion of flexibility. This framework will be refined and operationalized in the second part of this project.

Analytical Model: The flexibility of a system should be analyzed in two spaces, capability space and need space, and their interdependent relationship

Capability Space: Capability refers to the ability of a system to perform a task. For example, an airplane's capability consists of speed, load and range. Suppose that Ω_C is the sample space of capability. We can define sigma-field on the capability space. This sigma field contains enough information for decision maker. Let σ_C denote the sigma field of the sample space of capability. For example, when a component of capability space is expressed in real number, Borel set can be enough information set for the capability. If a component has finite number of feature, power set of the component set can be the information set.

Capability space is defined as a tuple of the sample space and the information set of capability, i.e., (Ω_C, σ_C). Every system has a representation on the capability space.

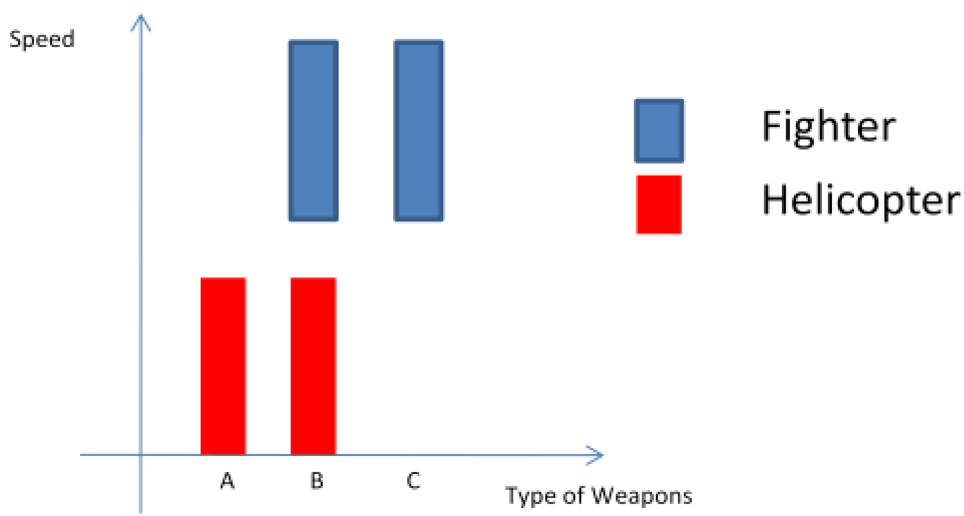


Figure 15: Capability Space Representations of a Fighter and a Helicopter

Figure 15: shows an example of capability space representation for a traditional fixed wing aircraft and a helicopter. Suppose that a decision maker interested in aircrafts. Among other features, the decision maker focuses on 2 features, the speed of aircraft and the weapon which can be installed to the aircraft. X and Y axis represents the speed of aircrafts and the type of weapons, respectively. The fighter can fly fast, but it requires minimum speed to fly. On the other hand, the helicopter is able to do hovering, although it can't fly at supersonic speed. With respect to usable weapons, above picture shows that a fighter can use B and C types of weapons, and a helicopter can use A and B types of weapons.

Note that the dimension of the capability space reflects the decision makers' interest. Suppose that a decision maker consider n aspects of the system. Then the sample space of capability is n-fold of sample space of each aspect. Let Ω_i^C be the sample space of i^{th} feature of the system capability, for $i = 1,2,\cdots,n$. Then the sample space of the system is expressed as $\Omega_C = \Omega_1^C \times \Omega_2^C \times \cdots \times \Omega_n^C$. In the same way, let σ_i^C denote the sigma field of i^{th}aspect. Then, $\sigma_C = \sigma_1^C \times \sigma_2^C \times \cdots \times \sigma_n^C$. A system's capability is configurable in the

capability space. It means that a decision maker can find a representation of a system (ω) on a capability space such that $\omega_C \in \sigma_C$

Need space: Need space represents the tasks that a system may/would be required to perform. This space depends on the end-users needs for the specific system, which may change over time. Capability space emphasized the engineering and manufacturing aspects of the system. On the other hands need space represents a user oriented point of view.

Let Ω_N be the sample space of need, i.e., Ω_N stands for the set of all possible needs which can be satisfied with a system. $\sigma_N$means the information set of needs. Similarly to the capability space, the pair (Ω_N, σ_N) is the need space. The dimension of the capability space is determined by the decision makers' interest. Suppose that there are m characteristics of need that is important to the decision maker. Then $\Omega_N = \Omega_1^N \times \Omega_2^N \times \cdots \times \Omega_m^N$. In the same way, let σ_i^N denote the sigma field of i^{th}aspect. Then, $\sigma_N = \sigma_1^N \times \sigma_2^N \times \cdots \times \sigma_m^N$. A need that is satisfied with a system is represented on the need space as ω_N, i.e.,

$$\omega_N \in \sigma_N$$

The need is closely related to the capability, and the relationship is expressed in a measurable function from capability space to need space. Let g be the measurable function, then $g: \sigma_C \mapsto \sigma_N$. Therefore the relationship between the capability space representation(ω_C) and the need space representation (ω_N) is $\omega_N = g(\omega_C)$
Since the function g is measurable, a decision maker can find an appropriate capability when a need is given, i.e., $\omega_C = g^{-1}(\omega_N)$.

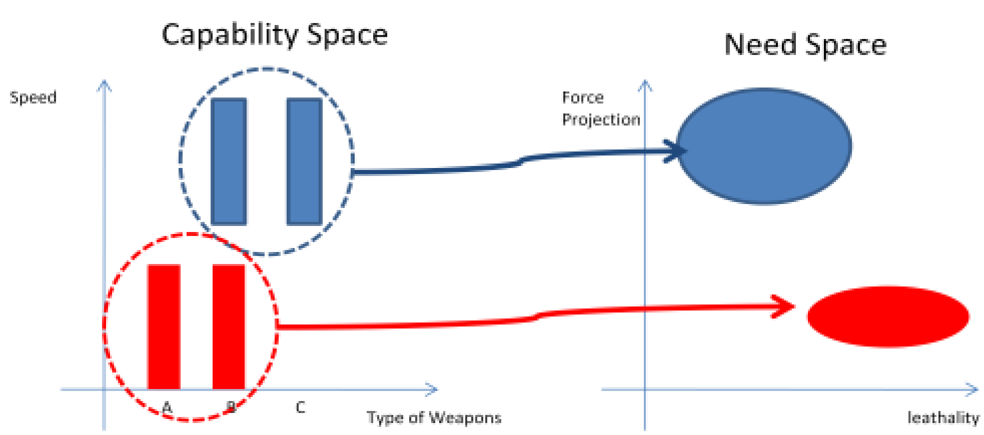


Figure 16: System Analysis

In previous example, we see the capability space representation of fighter aircraft and helicopter. Figure 16 shows the relationship between the capability space and need space. The 'force projection' and 'lethality' are the examples of the needs that those planes satisfy. Based on the capability representation (ω_C), a decision maker can find

the need that a system satisfies, (ω_N). The blue circle and the red circle on the need space means the need that a fighter aircraft and that a helicopter satisfies, respectively. A decision maker can find these needs by analyzing the capability representations of the planes.

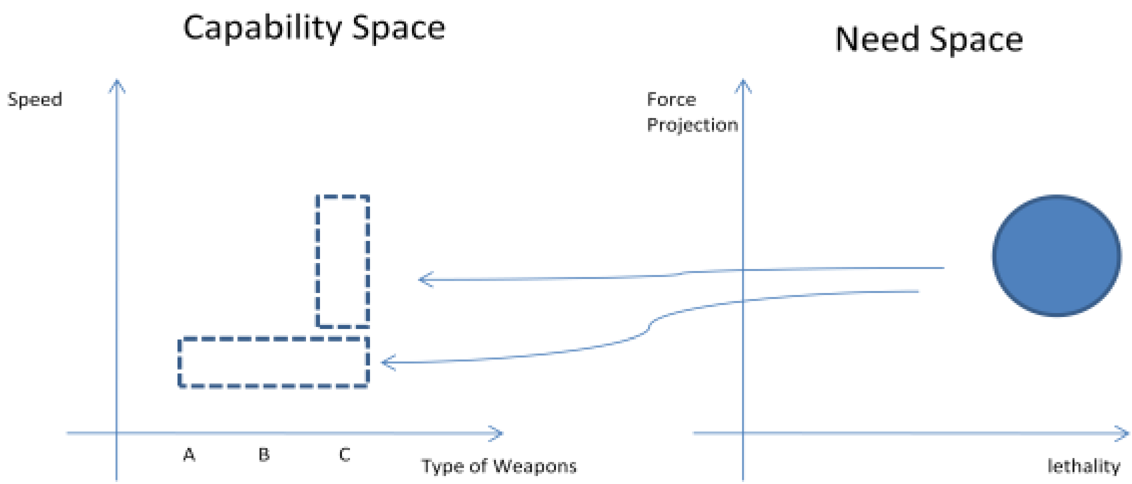


Figure 17: System Design

Its reverse is also possible. Figure 17 represent that the reverse procedure. Suppose that a decision maker want a system that satisfies the need represented by the blue circle on the need space. Then we can figure out what capability is needed to satisfy the desired need. Remark that the capability representation that satisfies a need may not be unique. In figure 17, two different systems can satisfies the required need.

Cost function: Cost function is defined on the capability space and represents the cost of achieving the capability of system. Cost includes dollars, calendar time, critical skills, and other scarce resources such as facilities, equipment and supplies. It also includes the costs of flexibility-induced decrements in other system attributes for instance performance, security, safety and usability.

The characteristics of cost are important information about the fits between environment and flexible system. For instance, suppose that architecture is very low cost in a certain range, but dramatically rise beyond the range. Then the architecture is suitable only when the possibility that out of range situation is occurred is very low.

How the cost can be measured has been a formidable task. Even in net present value method, one of the most famous decision rules, estimating future cash flow including cost is still controversial. The research of total cost of ownership will be helpful to clarify how to measure the cost.

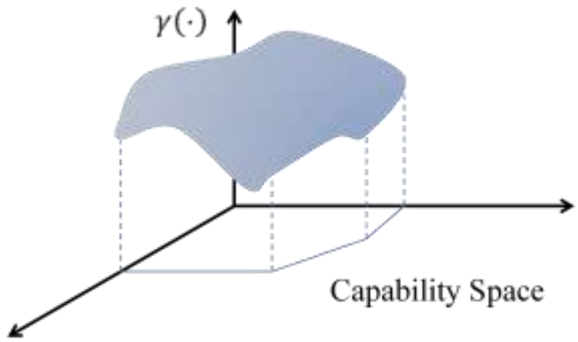


Figure 18: Cost Function

Future uncertainty on need space: Future uncertainty can be recognized on the need space rather than the capability space. For example, when we can find the probability distribution about future status, the probability distribution is defined on the need space. Let $\mathbb{P}(\omega_N)$ denote the probability distribution function.

Current models of the flexibilities depend on the assumption about future uncertainty. For example, Black-Scholes model assumes the geometric Brownian motion of its stochastic process and corresponding lognormal distribution of future statues. What if the process is not the geometric Brownian motion? 'What if' test and sensitivity analysis may provide valuable information to decision makers. In this sense, imposing general assessment of the future uncertainty is a merit of this analytical model. To illustrate this merit, an example of maximum entropy analysis will be posted on the appendix of this report.

Value function: Value function is a function from need space to a value space. Generally we can express the value of system in terms of real number. Then the value function V is a function from need space to the real line, i.e., $V: \sigma_N \mapsto \mathbb{R}$.
Since the future uncertainty generates the value of flexibility, the expected value of system is important. For well defined value function and probability distribution function, $V(\omega_N)\mathbb{P}(\omega_N)$ denotes the expected value of system.

The structure of analytical model: The Figure 19 illustrates the structure of analytical model. A system has a representation on the capability space. The cost function is defined on the capability space. Based on the capability, a decision maker can recognize the need that can be satisfied by the system. Moreover, when a certain need should be satisfied, a decision maker can figure out what capability is required to satisfy it. Future uncertainty can be recognized on the need space. The need determine the value of the system.

The analytical model is a general model of existing flexible models, such as modular system model, real options and value driven design approach. In later section, we will see how the existing flexibility models are interpreted in this framework.

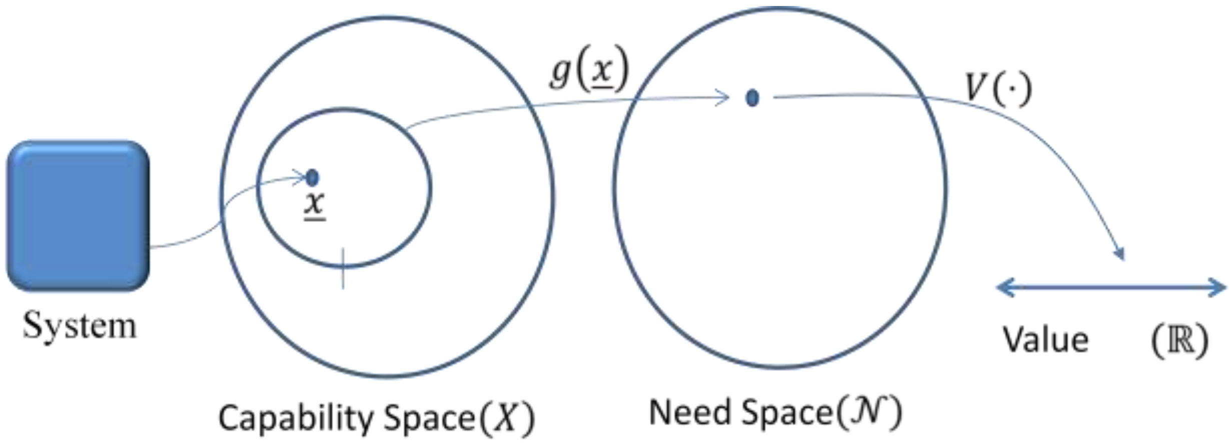


Figure 19: Analytical Model

Definition of Flexibility: Flexibility is the ability adjusting capability efficiently according to the change of environment. When a system changes its capability from $A$to B, its flexibility is defined as

$$Flexibility = \frac{\mu(A\Delta B)}{\gamma(A\Delta B)}$$

where$\mu(\cdot)$ and $\gamma(\cdot)$ means the measure of capability and cost function, respectively. $A\Delta B$means symmetric difference of A and B, i.e. $A\Delta B = \{x: x \in A \cup B \; and \; x \notin A \cap B\}$.

The flexibility has useful properties. The flexibility is a non-negative real number, $0 \leq flexibility < \infty$. Intuitively, a negative valued flexibility does not make sense, and this property catches the intuition. As the value of flexibility is low, the system is inflexible. When the change of capability, $A\Delta B$, is 0, the flexibility is 0. Suppose that changing the current capability of system costs enormously. Then the flexibility is small. On the other hand, when the change of capability is big and the cost of change is low, the flexibility increases.

To avoid infinitely big flexibility case, assume that $\gamma(A\Delta B) > 0, \forall A\Delta B \; s.t. \mu(A\Delta B) > 0$. Let's consider the product family design in terms of the analytical model frame work. When performances envelop is expanded by product family design, the flexibility is increased by increasing of numerator. Figure 20 shows how real option can be interpreted in this definition of flexibility. Real option is a right to change the capability in the future, therefore it increases the capability difference $\mu(A\Delta B)$ and enhances the flexibility.

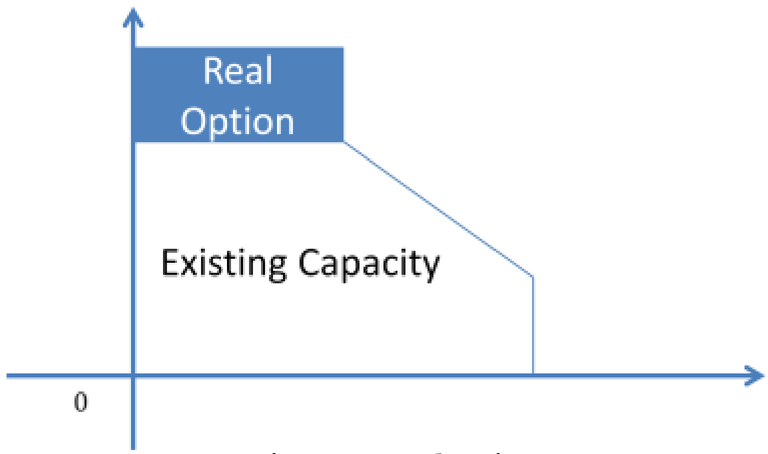


Figure 20: Real Option

Cost-down methods improve the flexibility. A typical example is a modular system. As shown in Figure 21, we can easily acquire new capability with modular system. This advantage is represented as the lower cost of required capability, comparing to the normal system. Since the modular system lower the denominator, $\gamma(A\Delta B)$, it increases the flexibility.

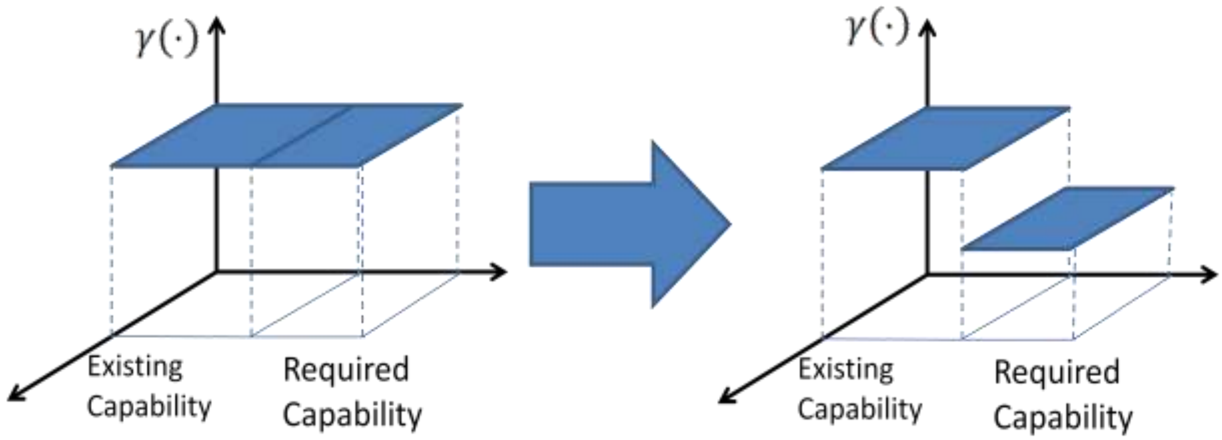


Figure 21: Modular System

Value of Flexibility: The value of flexibility is defined by the difference between the value of the systems which can be attainable and the cost to change the capability

$$V\big(g(A \cup B)\big) - \gamma(A\Delta B)$$

Note that $g(A \cup B)$ means the need that is satisfied with the flexible system.
Suppose that current system is A. The expected value of flexibility can be expressed as

$$\mathbb{P}\big(g(A \cup B)\big) \cdot V\big(g(A \cup B)\big) - P\big(g(A \backslash B)\big)\gamma(A \Delta B)$$

Where $A \backslash B = \{x: x \in A \text{ and } x \notin B\}$

Further discussion about cost function: When the cost of change is not symmetric, we need to consider it. $\gamma(\omega_1^C, \omega_2^C)$stands for the cost to change the capability of system from ω_1^C to ω_2^C. This cost function may be asymmetric. In other words, $\gamma(\omega_1^C, \omega_2^C) \neq \gamma(\omega_2^C, \omega_1^C)$.

Suppose that a new need should be satisfied through altering the system. Let ω_0 be the current capability of the system. A decision maker finds that both system ω_1 and ω_2 will be good for new need. Then what system should the decision maker choose? If $\gamma(\omega_0, \omega_1) < \gamma(\omega_0, \omega_2)$, then ω_1 would be the best choice, otherwise ω_2 would be the best. Suppose that there are n possible system changes,$\omega_1, \omega_2, \cdots, \omega_n$, to satisfy the new need. Then the rational change of system (ω_R) is defined as

$$\omega_R = \underset{\omega_1, \omega_2, \cdots, \omega_n}{\arg\min}\, \gamma(\omega_0, \omega_1)$$

4.3 Phase II Tasks and Research Deliverables

The primary goal of Phase I is to evaluate current flexibility valuation approaches and identify the limits of existing methods. To achieve these goals, RE-18 research team reviewed existing methods, processes and tools for flexible during Workshop I. As a result of this analysis, the RT-18 team found that the existing approaches provide useful tools to value flexibility. However, these approaches have several assumptions embedded in their formalism. These assumptions may not apply to the DoD system design and acquisition process. The existing approaches are not sufficient to answer the frequently asked questions such as "how can I value flexibility when the information about future uncertainty is limited?" or "how can I trade-off between flexibility and other performance measures?" Analysis of past cases confirms the inadequacy of present methods. Moreover, the valuation tools for flexibility have been developed for specific situations. It is difficult for a decision maker to answer the question "Which tool is appropriate in my situation?" Therefore, the need exists to define a comprehensive analytical formalism for defining and valuing flexibility that is better suited for use by decision makers in a DoD context.

In the next phase of the project, the RT-18 team will develop an analytical framework to assess the value of flexibility. Based on the model, the RT-18 team will develop an exemplary case study, implementing tools developed during the project. Each activity will be executed in complementary manner to each other. For example, the analytical model provides the basis of case study, and the findings from case study will be used to revise the model. Through these activities, the RT-18 project is expected to help decision

makers in a concrete manner. The Following figure is the roadmap of the RT-18 research project.

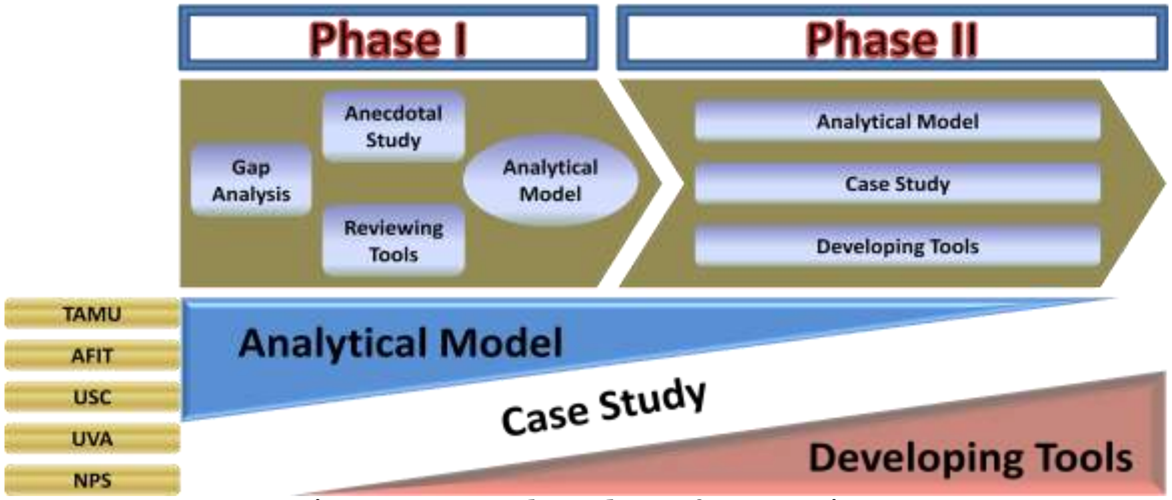


Figure 22: Research Roadmap of RT-18 Project

Although every team member will share their ideas intensively to contribute to this research project, each group will have one or more main domains to maximize the merit of the diversity of the RT-18 research team.

Action Items

- Case studies
    - Structured as a decision tree
    - What data is available?
    - What are the options?
- Methods
    - What are the inputs/outputs?
    - What does it measure?
- Analytical framework refinement

5 Summary

Despite its ubiquity in the literature, flexibility remains an ambiguous concept. There exist a multitude of definitions, which vary not only by domain, but within domains as well. Furthermore, these definitions often conflict with one another, making it difficult to discern the intended meaning in a given study, and nearly impossible to form generalizations across studies. Making matters worse, there is a plethora of related terminology that is often used carelessly and/or interchangeably with flexibility, thereby serving to further obfuscate its meaning.

Though the definition of flexibility may be convoluted, it remains highly sought after in system design. Flexibility is believed to provide a host of benefits, to include reducing risk, decreasing cost, improving responsiveness, enhancing capabilities, and extending system life. The literature also indicates a strong positive correlation between uncertainty and the value of flexibility. Given these ostensible benefits, and given that uncertainty is present to some degree in all acquisition programs, flexibility is increasingly viewed as a potentially powerful tool to mitigate those sources of uncertainty that perennially plague defense acquisition, such as changing requirements, unstable budgets, shifting technologies, and fluctuating policies. There is far less discussion, however, regarding the downsides of flexibility. Infusing flexibility into the design of a system is bound to require some type of investment or trade-off, whether that is additional cost, extended schedule, or reduced performance. The key point becomes whether the investment is warranted. This leads to the question of worth, and drives the need to quantify the value of flexibility in order to justify the investment.

We addressed the issue of quantifying the value of flexibility by reviewing the traditional approaches used to make decisions under conditions of uncertainty. We evaluated several potentially applicable techniques; most prevalent being real options analysis. However, the real options approach has several implicit assumptions that may simply be invalid or unverifiable in the DoD systems settings. These assumptions could lead to incorrect valuation and eventually incorrect decisions being made about investment in flexibility. In our analysis, we found that there is little unifying theory or guidance on best approaches to measure flexibility, quantify value of flexibility in a prospective systems acquisition or which MPTs work best in which situations.

Considering these major gaps in the current state-of-the-art the primary focus of our research activities is in developing a coherent value based definition of flexibility that is based on an analytical framework that is mathematically consistent, domain independent and applicable under varying information levels. Applying the principle of *value-driven design*, which is seeks to assess system value from a more strategic perspective, thereby inherently accounting for the value of non-traditional system characteristics like flexibility is potentially a promising approach for valuing flexibility. The next phase of this project will focus on refining the analytical framework and

developing a tool that can be used by systems acquisition decision-makers to conduct tradeoff analysis between flexibility and other system performance measures of interest.

APPENDICES

Appendix A: State-of-the-Art Survey

A.1: DEFINITIONS AND MEASURES OF FLEXIBILITY

The research literature on flexibility provides a many different definitions for the term flexibility and its synonyms. In order to provide a clear definition and a unified understanding of these different terms the following section provides an overview for each of the terms.

The first observation when analyzing the current literature is the fact that there does not seem to be a unified definition on what flexibility represents. Depending on the authors the terms ”flexibility”, “adaptability”, “agility” and ”reconfigurability” are used as synonyms. Following the definition overview this section also highlights the different quantitative methods used to measure system flexibility.

Rajan et al. [2005] for instance defines product flexibility as the degree of responsiveness for any future change in a product design. This degree is based on the flexibility of a design for a given change, the probability of occurrence and the readiness of the company to react to this change. From these factors the “Change Potential Number” (CPN) is determined using the change modes and effects analysis (CMEA) method. Nilchiani [2005] defined flexibility as the ability of a system to adapt to uncertain internal or external changes affecting its value delivery, in a timely and cost-effective manner. In other words, flexibility is the ease with which changes in value delivery in a system can be addressed. Here ease refers to the cost-effectiveness of addressing change. The elements of flexibility are system boundary, time window of change, flexibility aspect, system accessibility, uncertainty, and responses to change in the value delivery of the system. They form the basis for the measure of flexibility framework, which consists of the problem definition, suggested solution set, technical design model, economic evaluation model (Real Options Analysis), and finally the flexibility trade space exploration showing the value gained through implementing an alternative vs. the associated cost.

McConnell [2007] argues that while flexibility requires an outside agent as an effector for change, an adaptable system can change from an internal effector. They go on to argue that the difference between flexibility and adaptability seems only to reside in where the agent that effects the change resides - external or internal to the system.

An additional definition for flexibility is provided by Brown and Eremenko [2008]. They state that flexibility is the ability of a system to change on demand. This incorporates scalability, evolvability, maintainability, and adaptability. The proposed approach to achieve flexibility suggests fractioning systems. The resulting fractured system provides the ability to easily fulfill the above stated capabilities. Its gain in value (the total lifecycle value delivered by the system) is compared against the monolithic approach using Net Present Value (NPV).

According to Bordoloi et al. [1999], adaptability is the ability to change (e.g., to improve performance over a period of time) within a given state. Their definition further distinguishing between ability to change within a state (adaptability) and ability to change from one state to another (flexibility).

The following research papers provide definitions for adaptability. Mark [2005] argues that adaptation is the enhancement or change of a fielded system. If such a change has a low cost-benefit ratio, as defined by the customer or market, the system is deemed flexible. Based on stakeholder requirement Optimal Point Designs (OPD) are designed. These OPDs are compared to Multi-Mission Capable designs (objective function includes the functional requirements for each mission). Based on the performance gap, captured by the value of the objective function, an “optimal “ MMC is selected. Gu et al. [2004], for example, describe design adaptability, and product adaptability. Where design adaptability refers to the design paradigm, which is defined as the ability of a product to adapt to new requirements by means of small design changes that do not require a lot of effort. The product adaptability, on the other hand, refers to a product that is adaptable by the user. Chung and Subramanian [2004] refer to the adaptability of a system as the ability to accommodate change in its environment. Olewnik et al. [2006] define an adaptable system as one of two modes of a flexible system. The two modes depend on whether the operating conditions or requirements change in a predictable or unpredictable way. Systems that are able to accommodate an unpredictable change are called robust. In case of a predictable change to the system it is referred to as adaptable. Gu et al. makes a similar distinction of adaptability as Olewnik, however, they define the adaptability of a product/system with respect to foreseen or unpredictable change as specific adaptability and general adaptability respectively. Olewnik et al. further distinguish an adaptable system as one where the change can be either made in real time (active) or when the system is not in use (passive).

Chmarra et al. [2008] follows a similar definition as Gu et al. with respect to product live-cycle adaptation. They distinguish between adaptability during design and adaptability when the product performs a task, and refer to these as design-time and runtime adaptability respectively. Oppermann [1994] makes a distinction between an adaptive and an adaptable system. Where an adaptive system can configure itself automatically according to user needs. The adaptable system, however, requires user interaction to a change in the environment.

Finally, the last synonym used in conjunction with flexibility, reconfigurability, is defined as follows. A reconfigurable system, according to Ferguson and Lewis [2006], is one in which variables can be changed in real-time based on changes in operational conditions or requirements in order to maintain a high level of performance. The Initial starting condition is the design of optimized systems based on each known operation condition or objective. Based on stability conditions for the system trajectories are determined between the OPDs. Finally a controller is used for effective trajectory tracking (based upon a linear quadratic regulator approach).

Schulz et al. [2000] provides definitions for flexibility, robustness, adaptability, and agility in relation to system intelligence. According to their definition flexibility represents a system that can be changed easily and without ill effect. Agility is defined as the speed of change. However, agility is also the evolutionary level of flexibility. A similar definition is derived for robustness, which a system is if it is not affected by changing environments, and adaptability, characterizing a systems ability to adapt itself under changing environments.

The definition of agility can be further separated. Haberfellner et al. [2005] provides a detailed definition between agile systems engineering and agile systems. The former focuses on the alternative design space exploration during product development. The latter case describes the systems ability to respond to changes in requirements after initial fielding.

Given the above definitions for flexibility and its synonyms, the following provides an overview of how flexibility is measured in the current literature. Based on the previous definitions, flexibility is about the potential to change, and thus, unlike system performance, it is difficult to observe and measure. It is a potential that is not observable under nominal operating conditions.

In the context of manufacturing, for instance, flexibility of production systems is measured using Perti Nets, Decision Theory, Economic Consequences, and Physical Characteristics. Other methods to quantify manufacturing flexibility such as routing, operations, and loading incorporate the use of entropic measure (see Yao [1985] and Kumar [1987]). Methods to measure flexibility outside the manufacturing realm, however, vary based on the system under consideration. For example, if the flexibility measure is to be applied at the early design stage, Cormier [2008] proposes the use of a flow analysis table to rate the flexibility of designs. Thurston [1991], instead, develops a formal Methodology for the Evaluation of Design Alternatives (MEDA). The roots for Thurstons method can be found in classical utility theory. Another approach, taken by Gu et al. [2004] and Mark [2005], to measure flexibility is based on some form of performance measure. In the first paper the normalized savings of the flexible product are compared to those of the dedicated product and in Mark's paper the cost to realize the change becomes the basis for comparison.

Additional methods and their respective shortcomings in measuring system flexibility are discussed in greater detail below.

- Flow analysis tables characterize the interdependency of components and provide a quantitative flexibility metric for product flexibility with respect to flows between subsystems, interfaces between different subsystems, and the overall product layout. However, it assumes different areas of flexibility are independent, and that the design space is mapped linearly to the performance space.
- Entropy measure is applied to processes in the manufacturing context to determine various dimensions. Entropy measure, however, is ill suited for measure of flexibility since it does not consider that small number of outputs may be more different in kind from each other than a large number.
- Overlap Measure Method is a metric that combines the uncertainty range of the attribute value for a given alternative and the decision maker's preference function for the attribute, to determine a dimensionless score. It uses utility theory to measure the requirement satisfaction. Its limitation lies within the condition that it can handle at most one decision maker.
- The Generalized Information Network Analysis (GINA) compares multiple design alternatives on a common basis. It uses information theory to assess the performance of systems during operation. However, the use of information theory to model Concept of Operations is limited due to the inability to capture physical translation.
- The distance measure along the Pareto Front represents the set of designs that are non-dominated across objectives. Distance serves as proxy for the 'cost' of flexibility. This method only considers the utility of the system in a static context and does not consider effects of context changes on the system. Consideration of context change, however, is essential to mitigate risk that comes from uncertain futures. Also, 'distance' as a measure of flexibility does not capture the complex relationship between individual design choices.
- Benchmark Evaluation, a method where Optimal Point Designs (OPD) are evaluated against Multi-Mission Capable (MMC) design and Platform Based Derivatives (PBD) with the OPD serving as an upper bound on the MMC/PBD, uses a normalized performance metric to measure flexibility of platform designs. This measure does not consider uncertainties due to non orthogonal performance basis resulting from multiple different platforms under uncertainty.

As one might expect, the definition of flexibility is "context-sensitive" [Kumar, 1999] and that its usage is "likely to be significantly different depending on the domain of applicability" [Saleh, 2009]. Yet there appears to be a field of application where the concept of flexibility has been extensively analyzed and its usage *might* be considered relatively mature [Fitzgerald, 2009; Saleh, 2003; Thomke, 1998].

Within the manufacturing literature, the definitions of flexibility tend to be somewhat more precise and more consistent. In fact, experts on manufacturing principles are

comfortable enough with the umbrella-term of "flexibility," that they have created a multitude of different *types* of flexibility to describe more specific flexibility-related parameters. And the definitions for each of these flexibility "subtypes" also tend to be fairly consistent. These flexibility subtypes include *mix flexibility*, *volume flexibility*, *material flexibility*, *product flexibility*, *routing flexibility*, and *operational flexibility*, just to name a few [Saleh, 2003; Baykasoğlu, 2009; Nilchiani, 2006; Ajah, 2005; Bordoloi, 1999; Saleh, 2001; 36 Saleh, 2009; Chryssolouris, 1996]. And while these terms tend to be internally consistent, they do not translate across domains. For instance, "product flexibility" and "operational flexibility" are likely to connote something very different to the acquirer and the operator than they do to the manufacturer [Saleh, 2009].

Of all the specific manufacturing-specific flexibility subtypes, none seems to be precisely what we are interested in exploring, though *mix flexibility* may be the most germane. It is defined as "the ability to manufacture a variety of products without major modification of existing facilities" [Saleh, 2003]. The basic notion of easily expanding capability is what we wish to achieve, and is central to most of the definitions that pertain to Design Flexibility.

Scouring the literature on flexibility, we find that all remotely viable definitions do share the common element of change. However, not all definitions agree that it must be the system that undergoes change in order for it to be deemed flexible. Moreover, the nature of the change, its source, when it occurs, and how it occurs are all potentially differentiating elements of the published definitions.

We do find, though, that the elements of the flexibility definitions can generally be wholly described by the answers to one or more (usually more) of the following five questions:

1. <u>Will the System Change?</u> This refers to whether the system under consideration must change in some manner to be considered flexible. The alternative is that the system does not necessarily change itself, but rather "accommodates" the instigating change.
2. <u>What Measure(s) of Change Efficiency Applies?</u> This aspect of the definition provides a description of how efficient the system change is, relative to resources like time and money.
3. <u>What is the Source of the Change?</u> Asking this tells us where the instigating change force is relative to the system, i.e., internal or external.
4. <u>Is the Change Foreseeable?</u> Aims to capture whether the potential change is one that can be anticipated.
5. <u>When may the Change Occur?</u> This question relates to when in the system's lifecycle it may be exposed to the change, with the delineation being whether the change occurs before or after the system is fielded.

By way of example, let's use this construct to parse one of the most comprehensive definitions in the literature. In discussing design flexibility, [Saleh, 2009] states it "will allow the system to be easily modified should these requirements change after it has been fielded," and that "The requirement changes can be known or unknown upfront" (emphasis added). Posing the five questions above to Saleh's definition—

1. Will the System Change? Yes. The product has the capability to be "modified."
2. What Measure(s) of Change Efficiency Applies? The efficiency of the change for this definition of flexibility is qualified only in terms of "easily"; some of the definitions below will provide greater specificity for this parameter.
3. What is the Source of the Change? "Requirements" are the source of change.
4. Is the Change Foreseeable? The change may be anticipated (i.e., "known") or unanticipated (i.e., "unknown").
5. When May the Change Occur? The change would need to occur during the system's operational phase, i.e., "after it has been fielded"

Applying this framework to all definitions encountered which were at least marginally useful yields the following general results, and can be viewed in aggregate in Table 1.

Will the System Change? Among those scholars who believe that a system change is integral to the definition of flexibility, some are relatively specific, describing the system as being "modified" [Lafleur, 2010; Saleh, 2009; Thomke, 1998], "redesigned" [Rajan, 2003; Keese, 2007], or "reconfigured" [Olewnik, 2001]; others are more vague, referring to changing performance [Roser, 1999], the ability to "adapt" [Fitzgerald, 2009; Nachtwey, 2009; Merriam-Webster Online Dictionary 2010], or simply the ability to change [Brown, 2009; Shah, 2008; Bordoloi, 1999; Schulz, 1999. Again, it should be noted that when authors choose to define flexibility in terms of "adapt" or "adaptability," the result is rarely elucidating.

Other authors, however, do not explicitly state that a system must undergo a change in order to be considered flexible. One of these authors makes no reference at all to system change [Viscito,Lauren 2009], while the remainder seem to be indicating that for a system to be considered flexible, it merely needs to *accommodate* external changes. For example, these sources may refer to the ability to "support new functions" [Banerjee, 2004], "accommodate new requirements" [Sivanthi, 2008], or "to respond" [Nilchiani, 2006; Qureshi, 2006]. Interestingly, the fact that this could be a potential point of confusion is not addressed explicitly in the literature, but this is a crucial distinction. In practice, the question of whether the system must undergo change in order to be considered flexible is essentially the difference between overcapacitizing the system from the outset and "scarring" it for expansion (see *versatility* discussion at the end of this chapter). Using the analogy of computers, it is the choice between initially providing more memory than required and providing an expansion slot for additional memory should it be required later. If, in fact, both approaches may be considered flexible, then we need clarifying terminology regarding the type of flexibility to which we are referring as the two approaches have markedly different implications for system

design, development, operations, and maintenance. While overcapacitizing is one way to view this approach to achieving flexibility, another way to view it is to see it as providing appropriate capacity for a broader range of applications. Continuing the computer analogy, we could state that an Apple iPad is more flexible (perhaps more correctly stated as more versatile) than the Amazon Kindle e-Reader because it has a full featured web browser and media player included in the device. A laptop computer may provide even greater flexibility (or versatility) than the iPad by virtue of its ability to run additional software and support external devices (although one could argue that each of these provides an increasingly degraded reader function). This discussion of versatility and its relationship to flexibility will be discussed further at the end of this section.

What Measure(s) of Change Efficiency Applies? A majority of the useful definitions in the literature qualify the definition of flexibility in terms of its efficiency. Some qualifiers are generic, such as change with "ease" or "easily" [Lafleur, 2010; Schulz,. 1999; Saleh, 2009; Rajan, 2003], "effectively" [Nachtwey, 2009], "degree of responsiveness" [Qureshi, 2006], or simply "ready" [Merriam-Webster Online Dictionary 2010]. Several other definitions are more specific using temporal qualifiers like "timely" [Saleh, 2009; Nilchiani, 2006], "quickly" [Keese, 2007] or "real-time" [Olewnik, 2001] and monetary qualifiers like "cost-effective" [Nilchiani, 2006; [Saleh,[2009; Keese, 2008; Sivanthi, 2008] and "inexpensively" [Keese, 2007]. A few others just combine the two concepts into a single phrase like "minor time and costs" [Roser, 1999], and "incremental cost and time" [Thomke, 1998].

It can be argued that definitions that lack any qualification of how easily the change can be effected are of dubious value. For instance, when Fitzgerald [2009] says that flexibility is the "ability to adapt to new circumstances," one wonders what system does not have the ability to adapt given enough time and money. Under this conception, every living organism is flexible merely because it exists, and thus has successfully adapted to new circumstances. But without any way to discriminate the degree of flexibility among organisms, the definition can be of no analytical value. Providing some indication what we must invest in order to implement the system change is critical if we are to have any hope of quantifying the value of flexibility.

What is the Source of the Change? Just over half of the flexibility definitions indicate what source, or sources, may instigate the change in the system. The basic distinction is between "internal" or "external." Most authors do not explicitly state what they mean by internal and external, but from those who do in combination with other contextual clues, it is evident that an internal change is one that is inside the system boundary such as different operating modes, or the deliberate implementation of new designs. Similarly, external change appears to refer to those changes that occur outside the system boundary, but still affect the system, with the most obvious example being the operating environment. Several authors also characterize requirement changes as a valid source of change, but since it could be argued that requirement changes may be driven either internally or externally, this category of source change is tracked separately.

Of the authors who chose to formulate their definition by characterizing the source of change as external or internal, all agree that flexible systems must at least accommodate externally-induced changes [Lafleur, 2010; Nilchiani, 2003; Nilchiani, 2006; Olewnik, 2001; Nachtwey, 2009; Viscito, 2009; Shah, 2008; Thomke, 1998; Ross, 2008]. Two sources also allow for the source of change to be internal [Thomke, 1998; Nilchiani, 2006]. Finally, a number of others specifically call out changing requirements as a valid source of change [Lafleur, 2010; Olewnik, 2001; Merriam-Webster Online Dictionary 2010; Keese, 2007; Saleh, 2009; Sivanthi, 2008], with all but one making no comment regarding the question of internal or external.

The source of the change is presumably linked to the type of change, which is ultimately what we are interested in. The types of changes that are likely to be induced externally are bound to be different—and most likely more numerous and more significant—than those that are induced from within the system. This aspect of the flexibility definition is important, as characterizing the types and sources of change that must be accounted for will necessarily help shape the techniques that can be used to make a system flexible.

<u>Is the Change Foreseeable?</u> Some experts felt it necessary to qualify their definition in terms of whether the change was anticipated or not. Of those that did, all five indicated that the source of change may be unknown [Fitzgerald, 2009; Nilchiani, 2003; Olewnik, 2001; Keese, 2007; Saleh, 2009]. Three of these five also felt that the source of change for a flexible system may be known as well [Fitzgerald, 2009; Olewnik, 2001; Saleh, 2009].

Whether a change can reasonably be anticipated is clearly important to the system designer, as “known unknowns” can more readily be characterized and mitigated through risk reduction techniques. “Unknown unknowns,” however, are axiomatically more difficult to prepare for and the designer may have to revert to less precise mitigation techniques grounded in heuristics and “best practices.”

<u>When May the Change Occur?</u> The final definitional element that provides a discriminator between the various flexibility definitions pertains to when the change may occur. The large majority of authors do not address this point, either apparently not regarding it as relevant, or tacitly accepting that the change may occur at any point in the system lifecycle. One author, however, feels that a flexible system need only respond to changes that occur after the system is fielded [Lafleur, 2010]. Here, Saleh’s careful distinction between “Process Flexibility” and “Design Flexibility” leads to the conclusion that *process* flexibility only applies to changes occurring “during the design process,” and *design* flexibility applies to the work done during development that allows “the system to be easily modified should these requirements change after it has been fielded” [Saleh, 2009].

A summary of all the definitions binned according to the five-question template is shown in Table 1.

Adaptability (and its Relationship to Flexibility)

Since our primary interest in this report is to study the concept of flexibility, the research on adaptability is limited to where adaptability is discussed in the context of—or in relationship to—flexibility. Thus, when searching for definitions of flexibility, the results were comprehensive; whereas when searching for definitions of adaptability, the results are constrained by the fact that both concepts must be addressed in the same work (this same caveat applies to all subsequent terminology as well, but will not be repeated). Nevertheless, there were still a decent number of sources that sought to define adaptability. And as we found in the case of flexibility, all of the viable definitions involve the concept of change. And while "adaptability" was often used interchangeably with "flexibility," the overall variance within the different definitions of adaptability was lower that it was for flexibility.

A review of the adaptability material quickly shows that the definitions are very similar to those of flexibility. Shah [2008] refers to the "subtle distinction between flexibility and adaptability" contributing to the overall confusion on terminology. Given the similarity, we can use the same framework we used previously to organize and analyze the flexibility definitions. Of note, question two is no longer applicable, and the parameters have changed slightly for question five.

1. <u>Will the System Change?</u> This refers to whether the system under consideration must change in some manner to be considered adaptable. The alternative is that the system does not necessarily change, *per se*, but rather "accommodates" the change.
2. <u>What Measure(s) of Change Efficiency Applies?</u> This question is not applicable to adaptability—strangely, none of the definitions qualified the measure of adaptability in any efficiency terms.
3. <u>What is the Source of the Change?</u> This question asks where the instigating change force is relative to the system, i.e., internal or external.
4. <u>Is the Change Foreseeable?</u> Aims to capture whether the potential change is one that can be anticipated.
5. <u>When May the Change Occur?</u> For adaptability, this question refers to a different parameter than it did for flexibility. For flexibility, we were interested in the point in a system's lifecycle where the change could be introduced. For adaptability, the question of "when" now refers to whether the system can effect the change in real-time, or must be taken offline.

<u>Will the System Change?</u> All but one source indicated that a required element of adaptability is for the system to change in some manner. As was the case with flexibility, the actual description of change varied in terms of its specificity, and included terms like "reconfigure" [Brown, 2008], "alter" [Ross, 2008], "react" [Haubelt, 2002], and even the redundant "adapt itself" [Schulz, 1999]. The lone exception was a definition that refers to "accommodating change" [Chung, 2004]. Based on just this

element of our definitional construct, there is no meaningful difference between flexibility and adaptability.

What Measure(s) of Change Efficiency Applies? Not applicable.

What is the Source of the Change? All but one source felt that the source of the change was relevant to the principle of adaptability. Unfortunately, the sources don't agree on the source. Four papers indicated that adaptability implies that the source of change is external [Olewnik, 2001; Schulz, 1999; Haubelt, 2002; Chung, 2004], while three other sources stated that changes related to adaptability must be internal [Ross, 2008; Shah, 2008; Brown, 2008]. Meanwhile, just one author made any reference to changes in requirements [Olewnik, 2001], whose focus was the software domain.

Even with the lack of consistency regarding this aspect of the definition of adaptability, we can discern some difference from flexibility. First, for flexibility, the source of change was overwhelmingly seen as being external, with only two of the nine authors who referenced the source of change indicating that an internal source could be a valid source of change for a system to be flexible, and in both cases, this was in addition to an external source. For adaptability, on the other hand, three of seven authors went with internal, and none said it could be either internal or external. Of note, two authors specifically used this criterion as a discriminator between flexibility and adaptability. Ross [2008] posits, "If the change agent is external to the system, then the change under consideration is a flexible-type change. If the change agent is internal to the system, then the change under consideration is an adaptable-type change." Shah [2008] concurs, arguing, "Adaptation is an internally initiated change, while flexibility is externally initiated." Taken together, there appears to be a nuance that adaptability is slightly more suggestive that the source of change is internal to the system. Here, Shah may provide additional clarity: "An adaptable system needs to incorporate the ability to decide to instigate a change, while in a flexible system the decision-making ability is exogenous to the system" [Shah, 2008].

Is the Change Foreseeable? For the definition of flexibility, many authors were concerned with the notion of whether the change could be anticipated. In the case of adaptability, this factor appears to be of little interest. Only one author mentioned this aspect of the definition, citing the applicability of "predictable situations" [Olewnik, 2001]. This may be another potential discriminator between adaptability and flexibility.

When May the Change Occur? With the new adaptability parameters, this question refers to whether the system can effect its change while in an active state (i.e., in operations) or whether it must be in a passive state (i.e., off-line). Only a couple of authors included this criterion in their definition, and their assertions were not quite in accord. Olewnik [2001] allows for the change to occur while in operations or off-line, while Haubelt [2002] argues that the change may only occur when the system is in operations. Of greater interest, however, is the tacit assumption among these and other authors that adaptability is only applicable to the operational phase of a system. While

they neglected to explicitly include this assumption in their formal definitions, contextual clues indicate that they felt adaptability was a concept that applied to operations rather than development [Schulz, 1999; Brown, 2008].

Based on the definitions found in the relevant academic literature, adaptability is a very similar concept to flexibility. Like flexibility, it refers to the ability of a system to change itself when confronted by a source of change. However, adaptability is distinct in that it connotes that the source of that change is internal vie external, and that the change should be encountered after the system enters operations, especially if the change can be effected while the system remains "online." Another distinction is that the concern over whether the change is foreseeable seems much less important when discussing adaptability. Finally, only flexibility is defined in terms of effecting the change by some measure of efficiency, though it's not apparent why this should be.

Table 2 provides the graphical summary of all of the adaptability definitions we have examined.

Robustness (and its Relationship to Flexibility)

While adaptability may be the term most often confused with flexibility, it is certainly not the only one. The relationship between flexibility and robustness can be muddled as well. One scholar asserts that "robustness" and "adaptability" are the two design components that enable a system to have flexible performance [Olewnik, 2001]. Another scholar asserts that robustness involves satisfying a fixed set of requirements, while flexibility is about satisfying changing requirements [Saleh, 2003]. Clearly, we need to clarify the meaning of robustness as it pertains to flexibility.

We again employ the same framework we used previously to organize and analyze the flexibility and adaptability definitions. Of note, the first question now focuses on the performance of the system, rather than its inherent characteristics, and the second question is again not applicable.

1. Will the System Change? This refers to whether the system under consideration will undergo a change in performance, with change being an *undesired* outcome.
2. What Measure(s) of Change Efficiency Applies? This question is not applicable to robustness—none of the definitions qualified the robustness in any efficiency terms.
3. What is the Source of the Change? This question asks where the instigating change force is relative to the system, i.e., internal or external.
4. Is the Change Foreseeable? Aims to capture whether the potential change is one that can be anticipated.
5. When May the Change Occur? As it did for flexibility, this question of "when" refers to when in the system's lifecycle it may be exposed to the change, with the delineation being whether the change can occur before or after the system is fielded.

Will the System Change? Every source agrees that for a system to be considered robust, it must sustain its performance when exposed to change. Some definitions are more explicit that the performance of a robust system may not change at all, asserting, for example, that "robustness involves satisfying a fixed set of requirements" [Saleh, 2003] and "robust systems deliver their intended functionality" [Schulz, 1999]. The phrasing in other definitions, on the other hand, does seem to allow for some leeway in system performance, e.g., "the ability of the system to continue delivering value" [Shah, 2008] or needing to "minimize the effect … on the performance of the system" [Phadke, 1989]. But whether system performance is truly fixed or is allowed to slightly degrade, it's plain that the salient characteristic of a robust system is that it must remain relatively constant when exposed to change.

What Measure(s) of Change Efficiency Applies? Not applicable.

What is the Source of the Change? The source of the change also appears to be a key component in the definition of robustness. With one exception, every definition indicated that an externally-derived change is a type of change that must be withstood, most often referring to the "environment" [Phadke, 1989; Olewnik, 2006; Carlson, 2002; Shah, 2008; Saleh, 2009]. As summarized by Ross [2008], "the more environments to which it is insensitive, the more robust the system." Marking a small departure from the consistency in the robust definitions thus far, approximately half of the definitions also allow for the source of change to be internally driven.

Is the Change Foreseeable? This appears to be another important parameter as nearly half of the sources felt that it was an important part of the definition, all of them agreeing that the type of change is one that cannot be reasonably foreseen.

When May the Change Occur? One-third of the sources considered here indicated that robustness only applies to a system once it has entered operations [Phadke, 1989; Olewnik, 2001; Schulz, 1999; Saleh, 2003].

From the literature, there does not appear too much in the way of a direct relationship between flexibility and robustness, though some authors have identified some linkage. Olewnik [2001] sees robustness, along with adaptability, as "modes of flexibility: "Adaptable systems are capable of accommodating predictable changes in operating environment, while robust systems are capable of accommodating unforeseeable changes in the operating environment." Meanwhile, Schulz [1999] views robustness as a prerequisite to achieve adaptability, i.e., "Adaptability is the evolutionary level of robustness." And Saleh [2001] notes the similarity between the concepts but is careful to articulate the differences as well:

"Although these two concepts [flexibility and robustness] refer to the ability of a system to handle change, the nature of the change, as well as the system's reaction to the change, in each case is very different: Flexibility, as defined herein, implies the ability

of a design to satisfy changing requirements after the system has been fielded, whereas robustness involves satisfying a fixed set of requirements despite changes in the system's environment or within the system itself."

Another author establishes the distinction based on the stability of system objectives and the nature of the operating environment. For an entirely straightforward design task involving fixed objectives in an unchanging environment, then the system principle is *optimization*. If there is uncertainty with respect to the environment, but the requirements are still fixed, then *robustness* is needed. If both the system objectives and the operating environments are uncertain, then *flexibility* is what is called for [Banerjee, 2004]. Saleh [2001] summarizes the difference between flexibility and robustness through the example of a satellite system. If our goal were to maintain existing, on-board functionalities "despite changes in software and hardware characteristics due to radiation impacts, malfunctions, aging, etc,." the system would need to have a robust design. If instead, we are to create "new functionalities on-board for changes in requirements occurring after launch, as events unfold, new environments are explored, and/or new data becomes available, etc" then we must have a flexible design.

Although the term, "robustness," was occasionally used a bit carelessly in the literature, when it was defined, the results were remarkably consistent. The one definitional outlier came from Dr. Sambur, the 2004 SecAF, who described robustness quite broadly, using terms such as adaptable, expandable, scalable, reliable, affordable, and modifiable [Ross, 2008]. This definition notwithstanding, it seems implausible that when some scholars use the term "robustness" as a proxy for "flexibility," they are misusing the former term. Rather, it appears more likely that it is just another example of imprecise usage of "flexibility," as the difference between the two terms is stark. Whereas flexibility (and adaptability) is about the system changing in the face of change, robustness is fundamentally about the system NOT changing in the face of change. Consequently, it would clearly be incorrect to refer to a system as "flexible" merely because it was capable of maintaining a level of performance in light of a stressing operational environment.

The summary of the robustness definitions is provided in Table 3.

Agility (and its Relationship to Flexibility)

Before beginning this next discussion on agility, a quick note on format. For agility, as well as all remaining terminology to be discussed, we abandon the five-question analytical framework that we applied to flexibility, adaptability, and robustness. This is because these upcoming terms are not well suited to the model, and/or there is not enough material to make the approach particularly elucidating.
Agility is yet another term that is sometimes associated with the concept of flexibility. From previous research, we find that agility—like the other "–ilities" discussed thus far—

revolves around change. In the case of agile systems, the focus seems to be on the speed with which the system can effect the change:

- "The ability of a system to make a change *quickly*." [Ross, 2008]
- "The ability to change *rapidly*" [Shah, 2008]
- "represents the property of a system to implement necessary changes *rapidly*" [Schulz, 1999]

Sieger [2000] conveys a similar meaning when examining the agility of an organization, but the element of cost is also incorporated: "the ability of an organization to respond quickly and cost effectively to unexpected changes in customer desire."

Unfortunately, other definitions are virtually indistinguishable from a definition of flexibility—

- "The ability of a system to be modified or adapt itself to wholly unanticipated operating conditions or functional requirements" [Banerjee, 2004]
- "The ability to respond with ease to unexpected but anticipated events" [Oleson, 1998]

Oleson's definition adds the additional challenge of forcing the reader to ponder how an event can be both "unexpected" and "anticipated." And the final definition views agility in a completely different light:

- "The ability to instigate change rather than react to it." [Upton, 1994]

Still others formulate definitions of agility that encompass adaptability, flexibility, and robustness [Dove, 2005]. In terms of the relationship between agility and flexibility, Schulz [1999] regards flexibility as "a prerequisite to achieve agility, i.e., agility is the evolutionary level of flexibility." Ross [2008] discriminates the concepts as follows: "Agility is a modifier describing the nature of the change, just as flexibility and adaptability describe the location of the change agent."

In general, agility is encountered much less frequently in the published literature than flexibility, but the terms are clearly closely related. Both concepts refer to the ability of the system to change, and both terms provide qualifications related to the source and nature of the change to be responded to. And in one respect agility is more like flexibility than adaptability is. Unlike adaptability, agility *does* include the element of efficiency, particularly with respect to the speed of change. For these reasons, it appears that agility may best be regarded as a clarifying component of flexibility, as in a flexible system capable of implementing a change very quickly (and perhaps inexpensively) would be considered highly agile.

Changeability (and its Relationship to Flexibility and Other "–ilities")

As if the existing change-related terminology was not convoluted enough, it turns out that an increasing number of authors have begun to discuss "changeability" as an umbrella term for the concept of system change. Nachtwey [2009] regards flexibility as a "subset of changeability," while Fricke [2005] and Shah [2008] argue that the four terms we have discussed thus far are the very same that comprise changeability: "Changeability is defined as the ability of a system to change easily, and can be decomposed into four categories: robustness, agility, adaptability, and flexibility."

Ross [2008] largely agree but replace "agility" with the terms "scalability" and "modifiability," and then expound the notion of changeability considerably. Starting with the basic idea that the "Changeability of a system is determined by how easily it can undergo various changes," they develop a framework that consists of three fundamental aspects of change: *change agents* (instigator, or force, for the change), *change mechanisms* (the path taken in order to reach state 2 from state 1), and *change effects* (actual difference between the origin and destination states). Tying this approach back into our earlier delineations of flexibility and adaptability, Ross, et al describe *change agents* that are external to the system (e.g., users, technicians) as flexible-type changes, whereas *change agents* that are internal to the system (e.g., automatic software updating) are adaptable-type changes. Meanwhile, scalability, modifiability, and robustness are each a category of *change effect*, "which are quantified differences in system parameters before and after a change has occurred."

Another aspect of the changeability research is the principle of how to "Design for Changeability," or DFC. As described by Schulz [1999], DFC also consists of flexibility, adaptability, robustness, and agility, and together these "strategic attributes … describe the degree of intelligence regarding the systems [sic] ability either to be adapted, or to react to changes itself."

Modularity (and its Relationship to Flexibility)

Modularity is undoubtedly a viable research stream in its own right. And while modularity has its own definitional challenges, its meaning is unambiguous enough and distinct enough from flexibility, that there is little chance of confusing the two terms. Yet, these two non-traditional system characteristics continue to be closely linked in the literature, with modularity routinely described as substantially contributing to design flexibility, product flexibility, and overall flexibility (e.g. Rajan, 2003; Nelson, 1997; Gershenson, 2003; Baldwin, 2000). If we could establish that there is, in fact, a correlation between these two terms, then extant studies on modularity may provide additional insights into defining, quantifying, and implementing flexibility.

We begin by examining the definition of modularity. The IEEE definition is "The degree to which a system or computer program is composed of discrete components such that a change to one component has minimal impact on other components" [Institute of Electrical and Electronics Engineers 1990]. This is a good start that manages to capture

a key element of modularity: component independence. But, the full meaning of modularity is richer. The best source for a discussion on the meaning of modularity is certainly Gershenson [2003], who provides an outstanding and seemingly exhaustive overview of existing research on the definition of modular product design and its putative benefits, concluding that there are really three central components to the principle of modularity:

1. *The independence of a module's components from external components*
2. *The similarity of components in a module with respect to their life-cycle processes*
3. *The absence of similarities to external components*

Viewed in this manner, it is easy to see why so many authors regard modularity as an essential enabler for achieving flexibility. In theory, these modular principles should limit the potential impact of a change, while simultaneously reducing the extent of ramifications in the system's response. More specifically, the independence of the components tends to isolate the impact of the change, the similarity of components tends to simplify the development and implementation of a response to the change (e.g., redesign), and the absence of similarities to external components expands the option space and simplifies the change propagation analysis. It is the principle of independence that is most crucial in this assessment [Gershenson, 2003] as "the greater the connectivity between systems, the greater is the chance that a change to one system leads to changes in other systems" [Eckert, 2004]. For all of these reasons, it seems sensible to conclude that a more modular system is likely to provide greater flexibility.

Also recall that a key aspect of a flexible system is its ability to respond to changes more quickly and/or cost-effectively. These are some of the same benefits that compel researchers and practitioners to laud modularity. The idea that a modular system should be able to incorporate changes more quickly or at a lower cost is advocated by a number of studies that have examined both modularity and flexibility [Rajan, 2005; Ulrich, 1995; Sanchez, 1996; Walz, 1980; Gershenson, 2003; Thomke, 1997; Ulrich, 1999; Fixson, 2005]. As Gershenson [2003] observes, “"By promoting interchangeability, modularity also gives designers more flexibility, with decreased cycle time, to meet these changing processes." Rajan states flatly, "design flexibility is directly proportional to the number of modules in the product" [Rajan, 2005].

Modularity experts have provided many other generalized reasons why modularity bolsters flexibility. The list is long, and includes assertions that modularity—

- "Multiplies design options through mix and match of modules" [Baldwin, 2000]
- Provides "manageable units of programs or hardware" [Nelson, 1997]
- "Reduces the redesign cost for any future change" [Rajan, 2005]
- "Helps to define the interfaces between components" [Stryker, 2009]
- Allows a system to "more readily adapt … by 'plugging in' new modules" [Gershenson, 2003]

- “Allows the 'mixing and matching' of modular components to give a potentially large number of product variations” [Sanchez, 1996]
- “Allows a designer to control the degree to which changes in processes or requirements affect the product” [Gershenson, 2003]
- Allows for “relatively few designs to meet [a] greater number of applications” [Walz, 1980]
- Leads to systems that “have higher adaptability and consequently have better survival rates under changing requirements” [Lipson, 2001]

In a study involving space systems like Hubble, Mir, and the International Space Station, and assessing responses to foreseen changes, it was found that, “Modular design and separation of functionality are recognized as likely flexibility-enabling characteristics” [Lafleur, 2010]. Schulz [1999] also advocate the premise that modularity is an essential aspect of flexibility. As part of their work, they provide a detailed list of “extending principles” which are said to comprise the concept of flexibility (and adaptability, according to the authors). These principles included—

- Autonomy: Characterized by objects, which are capable of providing basic functionality necessary to ensure their independence from the embedding systems
- Scalability: Based on elements independent from scale (fractals), architectures may be scaled upwards or downward
- De-Centralization: Based on loose coupling and strong cohesion

In terms of the contrasting of these two system features, Olewnik [2001] believes the key discriminator is “type of adaptability utilized.” For modular systems to achieve greater performance, adaptations must occur offline, whereas flexible systems can enhance their performance while online.

It should be noted that the multitude of cogent explanations for why modularity enables flexibility must be regarded as somewhat lacking. Essentially, the arguments are based on empirics and heuristics, lacking any solid theoretical justification. As Saleh [2009] observes, the association between modularity and flexibility is treated as “an intuitive or self-evident truth, although there is limited theoretical proof.” Surveying the literature, it is evident that our ability to measure modularity is more mature than our ability to measure flexibility [Gershenson, 2003; Holtta-Otto, 2007; Mikkola, 2007; Stryker, 2009]. For instance, Stryker [2009], in the context of their modularity study, suggest that modularity has four quantifiable elements: degree of coupling, reusability, reconfigurability, and extensibility. While focusing on the reconfigurability element, they develop a reconfigurability measure, and observe that higher reconfigurability measures and “minimization of pairwise constraints” will necessarily allow for greater flexibility. Studies like these yield promise that if a quantitative linkage could be established between flexibility and modularity, the opportunity arises to use modularity as a proxy measure for flexibility.

Before proceeding to the next "–ility," it should be noted that there were some cautionary voices regarding the limits of how much flexibility could be achieved with modularity, and potential conflicts between the two. The author who developed a large portion of the "changeability" framework believes that modularity should be considered separately from these other "–ilities," as it is better regarded as an architectural concept used as a means to achieving change, rather than a change agent or measure of change response [Ross, 2008]. Ethiraj [2004] readily acknowledged that some level of modularity is conducive to flexibility (he refers to this as "adaptive change"), but asserts, "excessive levels of modularity can, in the limit, stymie any possibility of adaptive change." Ross [2008] advises that while modularity can increase some aspects of system "scalability," other aspects may suffer due to the up-front investment costs of implementing modularity. Finally, there may be other tradeoffs related to modularization and flexibility:

"There appears to be a potential trade-off between the desire for modularity from a 'business' standpoint and the desire for high performance and efficiency in the technical domain ... a more modular product is likely to be larger, heavier, slower, and less energy efficient."[Holtta-Otto, 2007]

The implication is that if there are downsides to implementing modularity, and modularity and flexibility are indeed correlating design characteristics, then these same downsides are likely to apply to flexibility.

Interoperability (and its Relationship to Flexibility)

Like modularity, interoperability is a mature research topic. Also, like modularity, measures have been developed to quantify system interoperability, so there is again the prospect of using interoperability as proxy measure of flexibility. Unlike modularity, however, the link between interoperability and flexibility is tenuous.

Not surprisingly, there are a number of different definitions for interoperability. From IEEE, interoperability is defined as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged" [Institute of Electrical and Electronics Engineers 1990]. The Department of Defense states that interoperability is "the ability of systems, units, or forces to provide services to and accept services from other systems, units, or forces and to use the services so exchanged to enable them to operate effectively together" [Department of Defense 2001]. Ford [2007] recently provide a comprehensive review of definitions related to interoperability and found that the DoD definition was easily the most prominent.

With respect to a potential relationship between interoperability and flexibility, there is extremely little to be found. From the Schulz [1999] study introduced in the modularity section, one of the extending principles of flexibility reads, "Integrability: characterized by compatibility and *interoperability* applying generic, open, or common/consistent

interfaces." Assuming a relationship does exist between flexibility and interoperability, arguments could be made both for a positive and negative correlation. On the one hand, the capability to readily leverage other systems would seem to provide greater flexibility of responses. On the other hand, the link to the other system represents another possible path of incurring change, and maintaining the interface link might effectively constrain flexibility. Unfortunately, the dearth of published materials on this point forces us to only conjecture.

Miscellaneous Related "–ilities"

We will conclude this chapter on definition with a short summary of some miscellaneous related terminology:

Scalability: Brown [2008] describes scalability as the "ability to add components or capability to a system throughout its lifetime." In this view, it is akin to the concept of incremental deployment. A similar conception is provided by Ross [2008], whom we noted previously defines scalability in his discussion of changeability. Ross defines scalability as "the ability to change the level of a parameter." So, for example, if an engine were designed such that it can have three, four, six, or eight cylinders, it would be scalable along this set of parameters.

Modifiability: Ross then goes on to define modifiability as "the ability to change the membership of the parameter set." Extending the engine example, if we can add a second set of parameters related to weight (i.e., 1000, 1500, 1800, and 2600), then the engine is deemed to be modifiable (but again, the specific weights indicate changes in scale).

Evolvability: "Ability to replace components due to technology obsolescence" [Brown, 2008]. This essentially represents the "upgradeability" of the system.

Universality: This concept refers to the ability of a system to have broad application, i.e., to "be used in a variety of situations without change or modification" [Saleh, 2001]. Saleh is clear that this descriptor should not be confused with flexibility, which—as we have noted—mandates an element of change for the system. He exemplifies the distinction noting that a satellite that carries multiple payloads and performs multiple missions would be universal, not flexible. The term "universality" tends to be applied more often in the software domain. The broader term for this same concept appears to be "versatility."

Versatility: This term is typically used as a synonym of universality, denoting "a high range of capabilities' variety" [Fitzgerald, 2009]. The standard example of a versatile system is the Swiss army knife [Baykasoğlu, 2009]. Another example would be a pen capable of writing upside down in multiple colors. Most authors would not characterize the knife or the pen as flexible. Others probably would, though, given the following examples of putative flexibility:

- "Nike shoes provide flexibility to the customer in terms of color choice, customized emblems (such as college names, symbols, and mascots), and choice of sole designs." [Qureshi, 2006]
- "removable-bit screwdriver" and "modern adjustable chair" [Rajan, 2005]
- A pen with "three modes of writing – black ink, red ink and pencil" [Rajan, 2003]

As highlighted during the flexibility discussion on system change, the difference between a versatile system and a flexible system is crucial. Implementing capabilities at the beginning of a program above and beyond the stated requirements is fundamentally a different programmatic and design approach than providing a system with the capacity to expand its capabilities beyond the initial requirements at a later time. And while the user would undoubtedly prefer the versatile system to the flexible system (because there would be no need to wait for the capability to be implemented), this is likely to be non-optimal for at least two reasons. The first should be obvious. No system can be expected to provide all capabilities, so a decision must be made based on the likelihood of needing the capability and the cost of obtaining it. By providing additional capabilities not justified by formal requirements, the procurement entity is saying that it knows more about this cost-benefit relationship than the user—essentially indicating that they should own the requirements!

The more subtle reason is that there is inevitably a cost associated with overcapacitizing the versatile system. In fact, the question of whether overcapacitizing is a better option than scarring is analogous to the question of whether scarring is a better option than not scarring, and is at the heart of a real option. Intuitively, the cost difference between scarring and not scarring seems significantly less than the cost difference between overcapacitizing and scarring. Whether this is true in reality, and whether the cost would be warranted in certain situations must be a central focus of this research. Thus, while versatility might not be a valid aspect of the flexibility model, perhaps it is an appropriate aspect of the value model. Put in actuarial terms, and paraphrasing Nachtwey's interpretation of flexibility, when is it worthwhile to purchase the flexibility or versatility insurance options?

Before leaving the discussion of versatility, it may be useful to discuss versatility at the concept level, because versatility at the concept level may not simply be the result of overcapacitizing the system. A simple example may serve to illustrate this point. One approach to countering mobile theater ballistic missiles is to provide air defense systems (radars and interceptor missiles) that are capable of tracking and shooting down incoming warheads (this is often referred to as active defense). While this active defense concept may be effective in countering a current generation of missile threats, it may not be a versatile concept in that it may be completely ineffective against a new threat of mobile ground launched cruise missiles. Further, it may not be considered very flexible if it is very difficult to modify the radars and/or interceptors to provide a capability against cruise missiles. An alternative concept such as attack operations (going after the mobile launchers before or after missile launch with an air-to-ground

system) may be considered more versatile (or flexible) if it can readily be used (or easily modified and used) to counter a wide range of mobile missile launchers (ballistic, cruise, SAMs, etc.). The attack operations concept may be more or less effective against the initial requirement set associated with the mobile ballistic missile threat; that is not the point of this discussion. The attack operations concept in this case may be judged as more versatile (or flexible) when considered against a broader range of scenarios.

A.2: APPROACHES FOR VALUING FLEXIBILITY

Given the previous overview on definitions and methods used to measure flexibility the goal of this section is to review the current state of the art literature on valuing flexibility. It provides an overview of the different methods developed in order to enable decision makers to select the system which provides the best design to adapt to future uncertainty.

The current literature on valuing flexibility provides several methods to determine the value obtained through system flexibility. Peoples [2004], for instance, proposes a program valuation technique which is based on real options theory (geometric Brownian motion) to calculate E[NPV]. In a similar way Gonzalez-Zugasti et al. [1999] apply the Real Options concept to model risks and delayed decision benefits under uncertainty. They develop a quantitative measure of the value of different family designs to select the most appropriate design off all design alternatives.

Using Real Options as a component in their methodology to design and analyze flexibility in large-scale complex systems Silver et al. [2007] synthesize Real Options Analysis along with the concepts of Decision Theory, Network Optimization, and Scenario Planning into the concept of Time-Expanding Decision Network (TDNs). This concept provides a framework to quantify the value of system flexibility. It consists of five principle steps that evaluate different set of designs based and their switching cost using minimum cost paths through a network of chance and decision nodes until convergence.

A two stage optimized design process for flexible product platform components is developed by Suh et al. [2007]. They evaluate the best design based on the Net Present Value using Monte Carlo simulation. Another framework to measure the value of flexibility of fielded products is developed by Mark [2005]. He determines the optimal design by evaluating Optimal Point Designs (OPD) against Platform Based Derivatives (PBD). The valuation is based on the performance gap of the OPD versus the PBD.
The approach taken by Besharati et al [2006] differs from the previously described approaches in that it is based on customer expected utility metric to support the selected product design. They use a generalized purchase modeling approach to develop a Decision Support System (DSS).

However, several of the studied papers on valuing flexibility have restrictive assumptions about the system type to ensure analytical feasibility. This restriction comes at the expense of the applicability of the model. Furthermore, the method for selecting the underlying stochastic process that affects the value has not been defined clearly. Additional methods for valuing flexibility and their respective shortcomings are discussed below.

- Decision tree analysis provides a graphical representation of the decision process. It can generate insight even with little hard data. Thoroughly assessing market risks, however, is rendered harder in decision trees. This is amplified by the fact that the analysis most often is based on subjective rather than an objective market-based approach. The subjectivity is a result of the assumptions made during the cash flow estimation.
- Real Options Analysis calculates the value of project flexibility in a managerial context. It is useful in its ability to provide a financial value of having options for design trade-offs. However, Real Options can only access the value for one particular option. In a setting with multiple options for a single system Real Options is not able to determine (value) which option to exercise.
- Value Weighted Filtered Outdegree is a metric to identify valuably flexible designs in a tradespace. It relies on Multi-Attribute Tradespace Exploration (MATE) to evaluate the performance of many different designs in utility-cost space. However, the results of this method are dependent on the chosen transition rule. In addition, the metric is dependent on the tradespace sampling strategy used by the designer. Finally, the process is time consuming (costly) because it requires significant input from the stakeholders and domain expertise making it less likely candidate for the rapid study of system flexibility.

In order to overcome these shortcomings and focus on the identification and quantification of changeability the work by Ross et al. [2008] develops a framework that intentionally excludes the valuation of flexibility. They apply tradespace exploration in order to compare and determine which design is more changeable. By doing so they provide a framework that does not rely upon specific assumptions regarding how to collapse time, utility, cost, and uncertainty into a single metric. In order to value a specific design valuation methods can be applies on top of the proposed framework.

A similar focus is found in the work by Nilchiani et al. [2007]. They present a six-element framework for measuring space system flexibility. The ability of this framework is to value flexibility based on monetary or non-monetary value by relying on aspects of interest for evaluation. Baseline and alternative designs are evaluated using the appropriate evaluation methodology. They distinguish between crude uncertainty capture (Net Present Value), technical uncertainties (decision analysis techniques), and market uncertainty (option pricing theory). For the non-monetary case they propose decision tree analysis combined with utility theory or prospect theory.

<u>NPV</u>

Based on the literature, we know that the value of flexibility is positively correlated to uncertainty, such that the greater the uncertainty in the system, the greater the value a flexible design option is likely to have. So if we are to make any headway on quantifying the value of flexibility, we need the ability to make the best decision under conditions of uncertainty. Fortunately for us, this type of problem has been studied extensively in economics.

One approach is net present value (NPV) analysis. NPV is a standard method for determining the time value of money. It takes into account the net cash flow at a particular time *t*, as well as the *required rate of return* (also known as the *discount rate*). Thus, the expected cash flows are discounted at an interest rate that accounts for the time value of money as well as the project risk [Ekström, 2005]. Several studies use NPV as part of their effort to quantify flexibility, including [Kumar, 1999; Olewnik, 2006; Sivanthi, 2008; Suh, 2007; Brown, 2009].

For the most part, though, researchers tend not to be in favor of using NPV for decisions involving flexibility [Saleh, 2003]. While NPV is sufficient in cases of "low uncertainty, or [when] you have no scope to change course," [Copeland, 1998; Mayer, 2007], it is not appropriate for situations involving great uncertainty, as it assumes a predetermined path through an established set of alternatives. This is antithetical to flexibility, so a different method is needed [Ekström, 2005; Banerjee, 2004]—one that can take more decision options into account [Collopy, 2009].

Real Options

Enter the method of *real options*, which exists at the intersection of value and uncertainty. Economic theory defines real options as the "right, but not the obligation to take an action at a predetermined cost and at a predetermined time" [Shah, 2008]. Traditional methods to cope with the future uncertainty are mainly focusing on making accurate forecast for future uncertainty and preparing for it. However, present decision making environment is not only uncertain but also dynamic. Even though the forecasting was accurate in the past, it might not be valuable because of the change of environment. One of the efficient ways to react to dynamic uncertain situation is using real option. The terminology, "real option", implies that it is a counter part of "financial option" and the option is not traded in the financial market. As a result, the real option valuation often refers to the well-developed financial theory.

Because the system flexibility provides decision makers the ability to cope with future uncertainty, it has value. The valuation can be categorized into two groups; absolute valuation and relative valuation. Absolute valuation purely focuses on the elements of the real option such as the stochastic behavior of underlying asset. In contrast, relative valuation method concentrates on the relative value of the option rather than the value of itself.

The absolute valuation approach model the decision environment with stochastic dynamic system, for example, stochastic differential equations. The value of flexible decision opportunity can be obtained by solving the system. The stochastic dynamic programming was developed by Richard Bellman and others in the 1950s. To solve the dynamic equation, boundary conditions are needed. Samuelson [1965] provided a useful boundary condition as known as 'smooth pasting condition', in the context of economic decision making.

The relative valuation is also called as risk-neutral valuation or contingent claim analysis. The idea of this approach is based on the two assumptions. First, there are other investment opportunities whose values are known. Second, a synthetic portfolio which is identical to the real option can be constructed using the known opportunities. The theoretical background of relative valuation can be found in (Arrow 1970). From the seminal works of Black and Scholes [1973], Merton [1971] and Merton [1973], relative valuation has been the paradigm of finance. Cox and Ross [1976] and Cox et al. [1979] developed clarified the random walk representation of Brownian motion and used it for contingent claims valuation. The well-known numerical valuation method, 'binomial tree', was suggested in this work. A rigorous statement of risk-neutral valuation was provided by Harrison and Kreps [1979]. In terms of mathematics, contingent claims analysis works under the assumption that uncertainty over the payoff from the investment is spanned by existing assets. Duffie and Huang [1985] investigated the conditions required for dynamic spanning.

Because of analogous between financial options and real options, the evaluation method of financial option is widely used for evaluation of real options. The relationship between financial options and investment decisions has been an interesting issue. From a practical point of view, Mun [2006] provides summaries of the differences between financial options and real options in the following table.

Financial Options	**Real Options**
Short maturity	**Long maturity**
Underlying variable driving its value is equity price or price of a financial asset	**Underlying variables are free cash flows, which in turn are driven by competition, demand, management.**
Cannot control option value by manipulating stock prices	**Can increase strategic option value by management decisions and flexibility**
Values are usually small	**Major million and billion dollar decisions**
Competitive or market effects are	**Competition and market drive the**

irrelevant to its value and pricing	**value of a strategic option.**
Have been around and traded for more than three decades	**A recent development in corporate finance within the last decade.**
Usually solved using closed-form partial differential equations and simulation/variance reduction techniques for exotic options.	**Usually solved using closed form equations and binomial lattices with simulation of the underlying variables, not on the option analysis.**
Marketable and traded security with comparables and pricing info	**Not traded and proprietary in nature, with no market comparables.**
Management assumptions and actions have no bearing on valuation	**Management assumptions are actions drive the value of a real option**

Table 13: Summary of the Difference BetweenFinancial Options and Real Options

There is interesting work related to real options. The following are well-known examples.

Myers [1977] showed that firms' investment options are a component of their market value. Mcdonald and Siegel [1986] examined when the optimal timing of investment is. They considered the case that the cost of investment is onetime and fixed, and value of the investment follows a stochastic process. Marcus and Modest [1984] considered the case with operating costs in the context of agricultural production decisions. Mcdonald and Siegel [1985] shows that if price follows a geometric Brownian motion, a unit output project with fixed operating cost can be valued as the sum of an infinite set of European call options.

When the price or utility of a project follows a geometric Brownian motion, the difference between the expected rate of price growth and the risk-adjusted expected return has important meaning. Mathematically it is one of the conditions for existence of solution in the infinite horizon problem [Dixit and Pindyck 1994]. Economic meaning of this difference was investigated by Mcdonald and Siegel [1984]. When the commodity is storable, the convenience yield which accumulates to inventory holders should reflect the difference between two rated. Gibson and Schwartz [1990] and Brennan [1991] examined the stochastic structure of convenience yield.

Entry or exit from an industry and postpone or resume a task are important issues in the Real Options Theory. Brennan and Schwartz [1985] provide a general model of the decision to open, close and postpone a mining project whose price fluctuates over time. Dixit [1989] examined the decision of entry and exit.

Switching among alternatives is a traditional topic in real options. In the financial economics, Geske [1979], Geske and Johnson [1984] and Carr [1988] researched the optimal switching among a number of choices according to the change of economic conditions. Under appropriate assumptions, the combination of switching can be interpreted as a set of compound options. In the real options context, Fine and Freund [1990] studied a general two-period model with the choices of low cost specific capital or high cost all-purpose capital. He and Pindyck [1992] considered the subsequent expansion of capacity. Bentolila and Bertola [1990] investigated the optimal employment level with hiring and firing costs. Kogut and Kulatilaka [1994] examined the choice of multinational company that switching production from one country to another country according to the fluctuation of exchange rate.

Majd and Pindyck [1987] provided a continuous investment and time to build model. They modeled the case that a firm invests continuously until the project is completed, and investment can be stopped and restarted later without any cost.

Gaps between practice and current research

The dynamic programming approach usually assumes risk-neutral decision makers and uses the risk-free rate for the discount rate. However, if the decision maker is risk averse, it is necessary to either use an appropriate discount rate or to use a certainty equivalent benefit.

The relative pricing approach may not work in some situations. For example, when qualitative characters of the choices are important, risk-neutral valuation does not work. Suppose that the CEO of Ferrari is considering expanding the factory to manufacture the Ferrari with new technology. To evaluate the value of this investment opportunity, he constructs a synthetic portfolio of a brand-new factory in a developing country, such as China, and bonds. Maybe the monetary values of both investments are identical. However, the Ferrari which is manufactured in the Chinese factory may not be the Ferrari that we know so far. To evaluate investment opportunities, we can use a common unit, such as U.S. dollars. However, a common measure does not guarantee that the opportunities are exchangeable. Furthermore, is the money that comes from a developing country different then the money that comes from a developed country? Can we distinguish the cash generated by investing to a stock or a bond? For the finance field, relative pricing works well. But when we consider real-option, we need to check the qualitative property of the opportunity.

In addition, note that relative pricing works only for complete markets. In a complete market, every asset can be perfectly replicated with other assets in the market. It means that the totally "NEW" asset which is not replicable with existing assets cannot be evaluated with risk-neutral valuation.

There are a lot of scholars stating that the contingent claim can be priced through any asset regardless whether its synthetic portfolio is traded in the market or not. Among

those, Harrison and Kreps [1979] provide a rigorous mathematical proof, and Cox, Ingersoll et al. [1985] also concur with this opinion. However all of these works assume the complete market and do not consider the qualitative aspect of choice.

The binomial tree method is the most popular numerical method to evaluate the value of options. Most of binomial tree methods, for example, Cox, Ross et al. [1979] implicitly assume risk-neutral valuation. We need to be careful before using the binomial tree method for evaluating real options.

Copeland [1998] claims that only real options can "provide a theoretically sound tool for valuing" decision flexibility. In a manufacturing application, Ajah [2010] touts real options, "which incorporates uncertainty in a theoretically consistent manner," and "that the adoption of the real options approach early in the conceptual design process can offer to the designer, extra degrees of freedom of systematically considering and designing system elements." In an article about flexible on-orbit satellite servicing, Joppin [2003] uses the case of a satellite upgrade to create a dynamic framework based on real options theory to capture the flexibility of the on-orbit servicing paradigm. In the information technology domain, authors have also used the real options technique in an effort to quantify flexibility [Ekström, 2005; Kumar, 1999].

Another example where real options analysis is used to help account for the value of flexibility comes from the Defense Advanced Research Project Agency (DARPA). With the spacecraft development program known as F6 providing the backdrop, Brown [2008] discusses the need to calculate the variance in net value of a given architecture in order to perform architectural trades. This goal is essential to the F6 program, which proposes a revolutionary—and truly flexible—satellite architecture consisting of clusters of satellite modules, physically "fractionated," but connected wirelessly so as to be functionally similar to traditional monolithic satellites. To be able to compare the value of the two disparate architectural options, Brown uses real options theory, and employs the time-honored Black-Sholes model to mathematically express the value of various design options.

Collopy [2009] also advocates the use of real options as a decision-making model, but avers that Black-Scholes is only legitimate under certain conditions: "(a) the underlying asset follows a geometric random walk, which is to say its motions fall into a lognormal distribution, and movements in non-overlapping periods are uncorrelated; and (b) the underlying asset is traded on an efficient market, that is, a market in which there is no possibility for arbitrage." Collopy then notes that the second assumption contradicts real options, in general, and the first assumption does not apply to the defense industry. So, if we elect to use real options analysis in valuing flexibility, Black-Scholes may not be the appropriate model.

The F6 example highlights the two principal drawbacks with real options theory. Like any valuation technique, we must establish the criteria for evaluation, which is not always straightforward. For the F6 program, the attributes selected as evaluation

criteria included the degree of fractionation, the reliability of each module, and the modes of connectivity between the modules. The specific value assignments are then largely determined through stakeholder interviews. This infuses a high degree of subjectivity into the process, which relates to the second challenge of real options. As a predictive model, it is only as good as its inputs. If the inputs are of questionable validity, then so too will be the results. Also note that real options doesn't get us much closer to our final objective. While it can be useful if one knows the current cost of the option and the expected value at a later time, the fact is that, for design flexibility, we lack knowledge for both elements (although one could argue that we should know the current cost).

In the upcoming sections, we present methods of quantifying flexibility that use real options as the basis of determining value. Saleh [2009] cautions against this. He notes that while real options is useful, it simply cannot provide insight into how to embed flexibility into the system, and that many are using it inappropriately.

"It is important to note the difference between the value of an attribute, here flexibility, and the measure of that attribute. For example, how reliable a system is differs from how much its reliability is worth … Several authors, in their attempt to bring the Real Options mindset to engineering design, fail to recognise this ***distinction between the value of an attribute, such as flexibility, and the measure of that attribute****" (emphasis added).*

Saleh's observation is trenchant. Indeed, as noted in the introduction to this chapter, we will find as we progress that most authors do fail to make this distinction. However, this is not a fault with real options, *per se*, but rather an error in its application. We do need to quantify the value of flexibility, and it would appear that real options analysis is a vital piece of the flexibility puzzle. We have already noted the strong relationship between flexibility and uncertainty, and the principle of uncertainty is at the heart of real options analysis. Illustrating this linkage, one author chose to essentially define flexibility as a real option, i.e., "Flexibility therefore can be seen as an insurance premium which is paid at present in order to have a possible advantage in [the] future" [Nachtwey, 2009]. Real options analysis techniques are therefore likely to be crucial in the effort to justify the investment in flexibility.

The Option Space (Pareto, DSM, HOQ, DODAF)

One aspect of quantifying the value of flexibility is identifying and enumerating the many choices that are available to us during the design phase. This range of choices is central to the notion of flexibility [Chen, 1999], and it is known as the option space. Several authors have discussed methods to characterize it. The most prominent method, by far, is to construct the Pareto set (also referred to as the "Pareto frontier" or the "Pareto front"), which is the full set of optimum design points that results when one must account for multiple competing objectives [Olewnik, 2006], and thus represents "the best achievable tradeoff between capacity and lifecycle cost" [de Weck, 2003;

Hollingsworth, 2004] recommends the intuitive phrase, a "trade-off surface." Examples of flexibility quantification research in which Pareto frontiers are constructed include [Brown, 2009; Nilchiani, 2003; Roser, 1999; Ross, 2008; Haubelt, 2002; Lasserre, 1985; Chattopadhyay, 2009; Brathwaite, 2009].

A challenge with this approach is how to generate the spread of points along the Pareto frontier, especially for a large option space. "Because weighted sum methods have difficulty in finding and generating Pareto frontiers," other approaches have been suggested, including genetically-based evolving algorithms [Eddy, 2001]. Eddy argues for the suitability of this approach as "nearly all design methodologies incorporate the concept of evolving designs."

The question of how the Pareto frontier relates to actual design flexibility becomes the next concern. Olewnik, [2006] tackles this aspect of the problem, as part of his research effort to develop a "decision support framework for the design of flexible systems." One of his key goals is to quantify flexibility, and constructing the Pareto frontier is the first step, which provides the boundary of the design space: "The ideal flexible system provides optimal performance by configuring itself to provide the performance associated with the extreme points of the Pareto frontier." Olewnik then proposes that the measure of flexibility is equivalent to the "distance" between the extreme points of the Pareto frontier, though it's not clear why this should be. Intuitively, the distance between extreme points on the Pareto frontier would seem to better indicate the *range* of flexible design options, vice the system's actual flexibility.

Another challenge regarding the option space is to assess the nature and degree of interdependence between multiple design considerations and requirements. This is frequently accomplished by use of the Design Structure Matrix (DSM) methodology. The DSM was introduced three decades ago by Steward as a "framework for formally identifying and tracking relationships between design variables" [Steward, 1981]. Keese [2007] and Qureshi [2006] use DSMs for interdependence analysis as part of their patent study work on flexibility.

Since "a primary goal in basic DSM analysis is to minimize the number of feedbacks and their scope by restructuring or re-architecting the process" [Abdelsalam, 2007], it's no surprise that this technique has been used extensively in terms of assessing modularity [Lai, 2008; Sosa, 2005; Holtta-Otto, 2007; Clarkson, 2001; Ethiraj, 2004; Stryker, 2009]. Shifting the focus from workflows to information flows, a clearer understanding of interdependencies can emerge. The overlap with flexibility is clear as well, since DSMs can help identify how change propagates through a system [Eckert, 2004]. Clarkson [2001] utilizes DSMs in this way as a method for change prediction within the system itself, which can help determine the probabilities across the option space. In Rajan's study examining the relationship between flexibility and the degree of modularization, the DSM "facilitates a complete view of the product configuration in a reasonably concise format" [Rajan, 2005].

An alternative approach that may be used to identify design interdependencies is *House of Quality* (HOQ). HOQ is the fundamental design tool of the broader customer needs tool, Quality Function Deployment. The fundamental premise of the HOQ process is that all members of the product team need to work together from the outset in order to produce a product that best meets the customer's needs [Hauser, 1988]. By constructing a matrix that resembles a house (to include a roof), HOQ "provides a fast way to translate customer requirements into specifications and systematically flowdown the requirements to lower levels of design, parts, manufacturing, and production" [Haskins, 2007]. The particularly relevant component of this process is the Technical Correlation Matrix, which documents the relationships between customer requirements and system design solutions in an effort to identify where dependencies and conflicts are likely to exist or arise.

Another option that may be worth mentioning is the Department of Defense Architectural Framework (DODAF). The DODAF is a conceptual model that guides the development of system and mission architectures. It is intended for use by DoD managers at all levels to make key decisions more effectively. Central to the framework is the concept of standardized products known as "views" that allow for visualizing, understanding, and assimilating the broad scope and complexities of an architecture [Department of Defense 2009]. While there appears to be no discussion in the flexibility literature regarding DODAF, it is feasible that certain architectural views may be applicable in our attempt to characterize design interdependencies.

There are two particular DODAF views that may be of use. The first is System View-5a (SV-5a), *Operational Activity to System Function Traceability Matrix*. The SV-5a maps system functions back to operational activities, thereby identifying transformation of an operational need into a purposeful action. During requirements definition, the SV-5a plays a key role in tracing architectural elements associated with system function requirements to those associated with user requirements. The second potential view of interest is the complementary SV-5b, Operational *Activity to System Traceability Matrix*. This view maps various systems back to capabilities or operational activities, which serves to transform operational needs into purposeful actions performed by the system.

The SV-5 is certainly not a mathematically-based, rigorous method of transformation. In addition, it is more applicable to higher levels of abstraction such as the design of systems-of-systems. Nevertheless, the SV-5 construct and terminology are familiar to DoD program managers, and thus, may be well suited for depicting the results of a more formal mathematical transformation.

Characterizing the option space is a vital element of any attempt to quantify the value of flexibility. Tools and methods such as Pareto fronts, DSMs, and HOQ are featured prominently in the literature as ways to identify the boundaries and interdependencies of the design option space.

Value-Driven Design (and Decision-Based Design)

It perhaps goes without saying that the notion of value with respect to the system design is central to the goal of quantifying the value of flexibility. Therefore, of prime interest to us is the principle of *value-driven design* (VDD), which attempts to incorporate value metrics into systems engineering design. VDD is a movement to refocus systems engineering processes on the optimization of the overall system design, vice the optimization of specific system performance parameters. There is growing interest and research into VDD across industry and the DoD [Collopy, 2008]. Owen Brown employs VDD on F6, and provides an excellent summary of the concept (which he refers to as *value-centric design*):

"In traditional requirements-driven systems engineering process, design choices are based on whether or not the outcome will meet the requirements. All designs that meet requirements are equally good. All designs that fail to meet requirements are equally bad. .... Value-Centric Design chooses the best design whether or not individual attributes exceed a threshold" [Brown, 2009].

This distinction is likely to be extremely important if we are to allocate value to a non-traditional system characteristic like flexibility. To implement VDD, we must first develop a value model, which is the objective function for comparing the worth of one design to another [Collopy, 2009]. Value models are suitable for capturing the upside of uncertainty, departing from the standard reckoning of only the downside uncertainty via traditional risk management techniques. Thus, a VDD model could feasibly capture the value added by investing in a more flexible design because of the potential payoff later. Furthermore, if the value of flexibility can be quantified in units that are commensurable with cost, then meaningful cost-value tradeoffs can be made. In other words, VDD may help us with the critical task of directly comparing costs and benefits by assigning values to each parameter that have the same units of measurement (presumably dollars). Then the best (i.e., most cost-effective) design is simply the one with the highest expected utility [Brown, 2009].

Collopy provides the following explanation to help the reader envision the value model and how it is used:

"One way to think of the model is in terms of a high dimensional attribute space, where every attribute is an orthogonal coordinate axis of the space. Each design maps to a point in the space. The value model is a potential function on the space. The model assigns a single scalar value to every point in the attribute space, much as an electric field assigns to each point in physical space a voltage (electrical potential), or a flow field assigns to each point a pressure. The mapping forms a value surface over the space. Design changes that move the design up the value surface are good, even if they detract from some properties" [Collopy, 2003].

Again, we see this idea of increasing the aggregate value of the system, even at the cost of local performance decreases. Value-driven design is not yet used routinely in the defense industry, but the underlying principle represents a potential sea-state change in how the DoD would manage its programs. The fact is that the cost to develop and operate a system that meets certain requirements over a given time period is not a deterministic value. By valuing non-traditional system characteristics like flexibility, VDD essentially provides a more efficient and strategic approach to systems acquisition, providing a more accurate and integrated assessment of true system cost than other extant putative measures of life-cycle cost. Brown calls this new proposed measure of true overall system cost the "stochastic lifecycle cost" [Brown, 2007].

Virtually all articles that claim to quantify flexibility in system design are employing VDD principles to some degree (e.g., [Nilchiani, 2006; Ajah, 2010; Banerjee, 2004; Joppin, 2003; Hazelrigg, 1998; Ekström, 2005]). Some approaches are straightforward, and some are complex, even convoluted. Ultimately, though, the task is simple: We are presented with a cost-optimization problem whereby we must obtain the highest design value for the lowest investment cost. The problem, of course, is that neither side of the equation has been satisfactorily resolved. Scholars rarely tackle the cost side of the equation, i.e., the question of how much does it cost to implement design flexibility. And there are equally few, if any, approaches to address the value side of the equation, at least in monetizable metrics. Put bluntly, **we lack a consistent, practical, and valid method for assigning the value for each flexibility option**.

In fairness, there was one attempt to do exactly that. Acknowledging that an appropriate value measure of flexibility must consider uncertainty and risk, Olewnik [2006] employs the *Decision-Based Design* principle [Hazelrigg, 1998] and utility theory to assign value to each of the design options. Value assignments are achieved through a method of *Consumer Choice Theory* known as *Conjoint Analysis*. Selecting the best option then simply entails finding the alternative that has the highest expected utility. Olewnik's approach is intriguing, but his proposed method of valuation is far more applicable to a classical profit-centered approach, which is not the motivating principle for defense systems. It should also be noted that Olewnik's conception of flexibility is much more in line with our definition of adaptability, even describing the "ideal flexible system is one where all of the variables are (potentially) actively adaptable" [Olewnik, 2006]. Nevertheless, it may be useful as a starting point in our efforts.

Filtered Outdegree

Now that we've completed a basic review the applicable tools, processes, and methods, we can commence an in-depth examination of specific methods that purport to quantify flexibility.

Under Ross' changeability framework, flexibility is indirectly derived through the quantification of changeability. In order to quantify changeability, Ross first creates a

tradespace framework consisting of so-called “change events” that are characterized by three change elements:

- Change Agent: The force that causes the change. Recall from earlier that Ross discriminates between adaptability and flexibility based on the location of the change agent (i.e., internal change agents pertain to adaptability; external change agents pertain to flexibility).
- Change Effect: The difference in states before and after a change has taken place. Recall that Ross identifies three categories of effects: robustness, scalability, and modifiability.
- Change Mechanism: The particular path the system must take in order to transition from its original state to its changed state. The more change paths that a system may traverse, the more “changeable” it is.

According to this framework, each change effect essentially represents a different system design approach. In order to assess which design approach is preferred, Ross calls for a measure of “goodness” to rank alternatives, preferably a relatively rigorous measure, such as a multiattribute utility function. Like many other researchers, Ross generates a Pareto frontier of the highest value designs.

Graphically depicted, nodes can be used to designate system design options, with arcs drawn to denote transition paths. Each arc would correspond to a particular system design (i.e., potential change mechanism), and have an associated cost (in terms of dollars and time). Ross then introduces the term, “outdegree,” which he defines simply as the number of outgoing arcs from a given design. Each design has a particular outdegree number, which represents an objective value of that design, and “provides a mechanism for system designers to explicitly improve the potential changeability of a system. Ross refines the outdegree concept further by establishing the “filtered outdegree,” which is the number of outgoing arcs for a particular design where the cost is less than the acceptability threshold of a given decision-maker. Using this approach, we can then measure flexibility of a given design by calculating the filtered outdegree, but only counting the change mechanisms caused by external change agents.

The proposed framework is compelling, as it provides a core mechanism for assessing how much investment is necessary to obtain a certain amount of flexibility, and is to be commended for considering the cost side of the value equation. But it is also missing some key elements, including how to actually value changeability and flexibility (e.g., NPV, real options), as well as how to establish the cost of each transition path. Ross was aware of at least the former omission, describing it as a deliberate decision due to the vagaries of valuation. In his words, “Valuation of ilities as a single metric is an additional layer of analysis that can be put on top of the proposed framework,” but since “all valuation techniques rely upon specific assumptions regarding how to collapse time, utility, cost, and uncertainty into a single metric,” inclusion would “reduce the generalizeability of the framework.” This article also does not provide any

recommendations on how to identify potential transition paths, which is a nontrivial aspect of the design challenge.

Shah [2008] makes use of the outdegree approach as well, while also filling in some of the research holes. Shah uses a DSM-like tool (which he calls the Engineering System Matrix) to "find useful points to insert options in the physical architecture," thereby providing some guidance on identifying potential transition paths. Shah also endorses the use of real options to help determine the relative value of the various design options. Shah's view is that if the outdegree of a given design is perceived to be too inflexible, or too costly, then embedding the opportunity for real options into the design may improve the cost/benefit ratio, thus justifying the investment.

Shah also endorses a second technique for identifying aspects of the design that are most likely to change or be impacted by change. This technique, developed by Eckert [2004], investigates the role of modularity and its ability to stem the propagation of change. Eckert devises a metric called the Change Propagation Analysis (CPA) as a means of predicting the effects on the system of planned and unplanned changes. CPA can help identify system components that tend to absorb or magnify changes and thus allow "the designer to investigate how possible changes will impact the structure and behavior of a system design." By combining DSM techniques to identify design and change interdependencies, filtered outdegree to determine changeability, and real options to provide the contextual value, Shah seems to provide one of the most comprehensive approaches to quantifying (and valuing) flexibility.

Most recently, the filtered outdegree method has been refined still further by a colleague of Ross. Viscito [2009] coins the phrase, Value Weighted Filtered Outdegree (VWFO), which is "a metric that captures the utility difference between an originating design and its possible destination designs." Importantly, the VWFO must be defined in terms of the consecutive time periods of "fixed context and expectations"—called an "epoch"—that are then encapsulated into a time-ordered series known as an "era." Each era represents one possible timeline for the system, and can supposedly facilitate discrete analysis of system flexibility via a computer-based modeling technique that is said to enable evaluation of very large numbers of discrete designs in utility-cost space. Within this step, yet another technique is introduced known as Tradespace Network Analysis that is intended to assess a system's ability to change states. When all these factors are integrated, the VWFO is used to identify those designs with the highest utility, and thus the most "valuably flexible."

In all, the filtered outdegree research seems highly relevant to our established goal of quantifying the value of flexibility. The only weakness seems to be that it will not work if the decision-maker cannot specify where he wants flexibility. Consider the following pronouncement by Shah: "If a decision maker desires the system to be flexibly scaleable [sic] in image resolution, then only change mechanisms that result in a change in level of image resolution performance will be counted towards the calculation of the outdegree of designs in the tradespace network." But what if we simply don't know

which change mechanisms will do that? In reality, we often lack the ability to cleanly map the design space attributes onto the performance space. Ross seems aware of this potential criticism, and evasively stipulates that, "Desiring "flexibility" in a general sense is meaningless from a design perspective, since it is an inherently ambiguous term, and must be further specified in order to be quantifiable and testable as a design goal."

Change Potential Number

Driven by the need to characterize unpredictable change in a meaningful way that facilitates analysis Rajan [2003], proposes adapting the established method of calculating *Failure Mode and Effects Analysis* (FMEA) for this purpose. The idea is to take FMEA's systematic approach to identifying potential failure modes, and apply it instead to look for possible changes that may occur in the system under investigation. Rajan dubs this modified process *Change Mode and Effects Analysis*, or CMEA.

The first step in the CMEA is to decompose the system "in some rational manner so that it can be assessed for possible changes." Then, one must create a CMEA table in order to obtain the "Change Potential Number" (CPN) for the system (compare to RPN in an FMEA). The CPN is supposed to provide an indication of how easily a change can be incorporated, and is described as "the overall flexibility for a given change." Continuing to borrow from the established FMEA structure and lexicon, Rajan uses three factors to calculate a system's CPN.

- F: The inherent flexibility of a design for a given change
- O: The probability that the change will occur
- R: The Readiness of the developer to react to the change
- N: Max of (number of potential Change modes, number of potential effects of change, number of potential causes of change)

Each factor, F, R, and N, is subjectively evaluated on an interval scale from one to ten. CPN is then calculated using the following formula:

$$CPN = \frac{1}{N}\sum_{i=1}^{N}\frac{[(R_i + F_i) - O_i + 8]}{27}$$

To his credit, Rajan then selects ten consumer products as case studies to validate his model (a step omitted all too often in this literature). The ten products consisted of flexible products (i.e., "multiple external modules) and inflexible products (i.e., "more integral design with fewer modules'). After each product was decomposed in terms of its modules/parts, subjective scores were assigned—though only for one CPN factor (F, its inherent flexibility—more on why in a moment). Then the CPN score was calculated. Rajan considers the model validated at this step because the CPN scores for the products indicated relative levels of flexibility consistent with the judgment of "experienced designers."

Other authors have used the CMEA process when attempting to validate their research, including Qureshi [2006] and Keese [2007]. Finally, it may be worth noting that the research on CMEA has apparently not extended beyond its originating university (University of Texas at Austin).

The CPN metric, as described by Rajan, raises a number of concerns, both with the methodology, as well as the underlying theory. In terms of methodology, the probability that the change will occur (O), and the readiness of the developer to react to the change (R), both seem like they would be difficult to quantify, and the author doesn't explain how it might be done, even sidestepping the problem entirely by only considering the inherent flexibility factor (F) in his case study. Moreover, the validation approach manages to be both useless and invalid at the same time. Rajan conducts a functional decomposition based on modules, and then selects a series of products whose flexibility is differentiated based, in essence, on the number of modules. Then he chooses to omit the other CPN measures that he devised because obtaining them would require "a significant level of industrial interaction." It is no wonder that the results "validated" the model, as the model did little more than scale the input and call it an output. Furthermore—and perhaps most concerning from a theoretical perspective—Rajan provides no rationale for the CPN formula. It is presented, fully formed, without any hint of derivation or justification, so it's impossible to discern what theoretical underpinning, if any, applies.

Given these problems, we are left to wonder whether CPN is merely a difficult and subjective measure of product flexibility, or wholly illegitimate.

Flexibility Aspects

Fitzgerald [2009] studies flexibility in the manufacturing and information technology fields, and proposes a method to examine the "flexibility aspects" of systems in terms of the system's potential flexibility capabilities and the systems behavior under change. To obtain a system's flexibility aspects, the system must be decomposed along three distinct "flexibility dimensions."

- Range: Measures the variety of alternatives for a given change, i.e., the "action space"
- Response: The preparation time/cost for coping with a change in the action space
- Distension: The invested effort/time/cost for enhancing the current action space if needed thus enabling the generic object to accommodate a given change whose handling is currently outside the action space.

Note that under this conception, Fitzgerald's use of "response" is akin to "versatility" in that it measures the effort necessary to employ a latent capability, not develop a new one. Whether this is truly a system change is debatable, and it certainly isn't consistent

with most definition of flexibility. Distension, as defined here, is the concept we are interested in as it is the only dimension that relates to new capability. Unfortunately, what appears to be missing from Fitzgerald's approach is how exactly to establish and value distension, which is the crux of the problem.

Baykasoğlu [2009] uses a similar three-dimensional framework to quantify flexibility, but replaces "distension" with probability. To Baykasoglu, the inclusion of probability is vital, and is overlooked surprisingly often by other researchers. After all, he argues, the value of flexibility is a function of uncertainty, and thus the likelihood that a given change will occur must be taken into account. Thus, a system should not be considered substantially more flexible than another system simply because it can more easily accommodate a change that is very unlikely to occur. Although Baykasoglu is primarily concerned with manufacturing flexibility, he believes his approach has general applicability, "if properly implemented."

His approach involves creating a matrix that captures all possible states of a particular system, along with the efficiency of each state, and the probability of switching to a different state. From the resulting matrix, a value known as the "permanent" is calculated. The permanent is similar to the determinant, except that only absolute values of the diagonal products are used, so there are no negative components in the calculation. Its graph theory interpretation is the sum of weights of perfect matchings in a bipartite graph. Baykasoglu's approach would appear valid, but his explanation of the process lacks clarity. In addition, it seems likely that populating the probability and efficiency aspects of the model would be difficult in practice.

Flexibility Dimension

Cormier [2008] aims to provide flexibility metrics for use in the early stages of the system design process. Operating under the premise that, "the flexibility in the initial product architecture will largely determine the overall flexibility of the final system," Cormier ultimately wishes to provide a method for the designer to select the most flexible product architecture. The author proposes to measure flexibility along three dimensions:

- Flows between subsystems
- The connections between subsystems
- The geometry of a system

The *subsystem flows* are intended to capture the range of possible transfers of material, energy, or signal out of the subsystem into the target (i.e., design space). Then, "the various ranges of flow characteristics that a subsystem can handle are compared to target ranges to evaluate the flexibility of a flow." At this time, Cormier's model assumes that the mapping between the design space and flexibility is linear, but hopes to address nonlinear mappings in future research. The connections between subsystems are essentially an interface analysis, where higher numbers of interfaces, and interfaces that

do not provide functionality are penalized in Cormier's scoring methodology. Finally, the ability of the system to expand and contract to accommodate changes in functionality or performance is considered. Cormier refers to this concept as the system geometry, and involves constructing two matrices that are intended to capture the system's expansion and contraction characteristics.

These three dimensions then serve as the vertices of a flexibility cube in which the final flexibility rating is determined by its location in the space (a score of zero would be the most inflexible product imaginable). Unfortunately, it is not evident what value this measure is, or why it should be considered valid.

Flexibility Index

In his article on what he calls "developmental flexibility" [Thomke, 1998], proposes the use of a *flexibility index* to measure how well a given system responds to a particular change. The Flexibility Index is calculated by dividing the percent change in a given attribute by the percent change in projected profits. So, for example, if it costs five percent of projected profits to increase the battery lifetime of a product by twenty percent, then the Flexibility Index of this product for this attribute is twenty divided by five, which equals four. This results in a measure of the economic cost of modifying a particular product feature.

The flexibility index does provide a measure of investment cost—at least in terms of a ratio—which is good. Of course, the denominator of the ratio is not what we're looking for, as profit is not the motivating factor in defense acquisition. There are some other obvious concerns in using this approach for our purposes. First, the method of calculating the flexibility index, while logical, is not justified by the author via any scientific or mathematical rationale. Second, this technique is necessarily attribute-specific, thus only providing an indication of the system's ability to change with respect to a single feature, not an overall indication of the system's ability to accommodate change. To gain insight into the whole system, a series of flexibility indices would need to be calculated and amalgamated. Moreover, this approach is not applicable to cases of unforeseeable sources of change, which is also a drawback. Finally, and most fundamentally, the flexibility index doesn't measure any inherent characteristic of the product at all—it simply provides an indication of return on investment to facilitate a single attribute decision analysis.

Flexible Platform Design Process

One of the most comprehensive (though not entirely lucid) techniques is developed by Suh [2007]. He describes an end-to-end normative design process, which takes into account external sources of uncertainty to achieve flexible systems. The seven-step process, which mostly consists of organizing and collating existing methods, is called the Flexible Platform Design Process (FPDP). The steps are as follows:

1. Identify market, variants, and uncertainties
2. Determine uncertainty-related key functional attributes and design variables
3. Optimize product family and platform bandwidth
4. Identify critical elements for flexibility (change propagation analysis, engineering expertise)
5. Create flexible design alternatives (brainstorming, concept screening and scoring matrix)
6. Determine costs of design alternatives (Parametric cost modeling)
7. Uncertainty Analysis (Decision Trees, NPV, Real Options)

The first step uses clustering analysis and conjoint analysis. The second step can be accomplished via QFD. Step three is done via gradient-based optimization and heuristic optimization (not covered). CPA, or "engineering expertise" is used in the fourth step. Step five is accomplished via brainstorming. Parametric cost modeling is the recommended method for step six. And NPV or real options are leveraged at the final step.

With the possible exception of step four, Suh appears to have contributed little new content to the topic of quantifying the value of flexibility. Nevertheless, Suh's holistic approach is welcome, and as Suh notes, step four is a critical aspect of the problem. Suh reasonably argues that other methods jump to a valuation technique prematurely, failing to explicitly differentiate all the potential flexible design options in terms of which is likely to provide the greatest "bang for the buck."

The Formula for Flexibility

Occasionally, authors have provided an entirely mathematical conception of flexibility, thereby automatically allowing for quantification. We conclude our survey by summarizing two such approaches. One author defines flexibility as the "partial derivative of the total instantaneous cost with respect to a given state" [Bordoloi, 1999]. Another looks to identify the optimal flexibility/cost-tradeoff curve of a system using the following formula:

$$f_{\mathrm{impl}}(\gamma) = a^{+}(\gamma) \cdot \begin{cases} \left[\sum_{\psi \in \gamma.\Psi} \sum_{\tilde{\gamma} \in \psi.\Gamma} f_{\mathrm{impl}}(\tilde{\gamma})\right] \\ -(|\gamma.\Psi| - 1) \quad \mathit{for} \ \gamma.\Psi \neq \emptyset \\ 1 \qquad\qquad\qquad \mathit{otherwise} \end{cases}$$

Which he describes in words as—

"The flexibility of a cluster, if ever activated, is calculated by the sum of all its interfaces' flexibilities minus the number of its interfaces less 1, and 1 if there is no interface in the given cluster. The flexibility of an interface is the sum of flexibilities of all its associated clusters" [Haubelt, 2002]

While the purely mathematical approaches to quantifying flexibility are intriguing, it's far from clear that either conception has any practical merit. The first idea based on "instantaneous cost" doesn't seem relevant to design flexibility (though it claims to), nor does the above formula. In fact, the proposed formula seems instead to be a measure of component interdependence, which would be a submeasure of modularity, not flexibility.

Summary

The model for quantifying the value of flexibility needs to meet multiple criteria. First, it must be theoretically valid. The model we seek needs to be capable of correctly measuring the degree of flexibility in a system design (or proposed system design) and enabling credible value decisions in the face of uncertainty. Second, the model must be demonstrably valid. It must predict testable results, and allow for verification and validation via the application of case studies. Third, the model must be usable. Its outputs should be readily understood by decision-makers, and it should have the capability to be readily applied by practitioners, to include having data inputs that can be obtained in a reasonably straightforward manner, and with a minimum amount of subjectivity. Last, our ideal flexibility value model needs to be applicable to the DoD. Defense acquisition is fundamentally different from private-sector acquisition in that system value is not ascertained based on profit forecasts; rather, value is determined by a system's capabilities, and how well it meets warfighter needs.

This discussion shows that there are many general and specific tools, processes, and methods for developing such a model. While many of the framework tools may be useful to us, none of the fully-formed methods meet all of our criteria. Many are of questionable scientific validity. Several others may be valid, but fail to demonstrate their validity, or are too esoteric to allow for any possibility of genuine validation. Some of the most promising models are the most difficult to understand and most difficult to actuate (i.e., filtered outdegree, flexibility aspects, and flexible platform design process). And only a couple of techniques are well suited to the alternate value strategies of the military, while none included a defense-based case study. Most problematic of all, far too many of the approaches take aim at the wrong concept entirely, seeking to measure flexibility, *per se*, rather than the *value* of flexibility.

A.3: MPTs for Incorporating Flexibility in Systems

Following the overview of the different definitions of system flexibility, its measure, and the valuation of flexibility, this section focuses on the available methods, processes and tools to incorporate flexibility into system design or allow for fielded systems to be adapted to changing environment characteristics.

There are also several classes of MPTs for improving flexibility. These include modular and service-oriented architectures; domain ontologies; interoperability connectors;

autonomy and adaptive control; agile methods; concurrent engineering; robust optimization; delayed differentiation and user programmability. The following sections discuss some of these approaches in detail.

Modularity

A frequent—though perhaps overly simplistic—recommendation for achieving flexibility is to simply implement modularity. A number of studies come to this conclusion based on empirical approaches.

In response to our sponsors' priorities, our primary research focus will be in valuing the flexibility to adapt to foreseeable sources of change. For this case, a very powerful strategy is to modularize the system's architecture around these sources of change. For software, a strong theoretical and practical basis for this strategy was developed in [Parnas, 1979]. It has subsequently been found to work well for systems including hardware, software, and human factors. If this is done, when the foreseeable changes come, their adaptation effects are confined to single module.

Acting on the presumption that "flexibility is an existing property of certain products which results from design choices made by their inventors," two research projects chose to use the U.S. patent database as a means of collecting data regarding design choices for various inventions. Qureshi [2006] was the first, identifying and analyzing 90 patents. Based on his analysis, he arrived at a rather unwieldy set of seventeen new principles of flexibility, which he then binned (mercifully) into four broad principles:

- *Increase the degree of modularity of a device*: This recommendation included obvious suggestions like "using a different module to carry out each different function" and "dividing each module into a number of smaller, identical modules"
- *Reduce the communications between modules and enable the device to function normally regardless of the orientation, location and arrangement of its individual modules*
- *Facilitate the addition of new functionality*: This included the recommendation to locate "those parts which are anticipated to change near the exterior of the device and those which are not near its center"
- *Enable the device to respond to minor changes*

There's really not a lot to be learned by these recommendations on how to make a product more flexible. The first two suggestions can be summarized as, "make the product more modular," and the last two are tautological, essentially saying, "make the product flexible."

Keese [2007] expanded on Qureshi's patent work by merging it with an empirical study of various consumer products that were also deemed to be flexible. Interestingly, he uses CMEA to identify flexible design aspects. He arrives at a very similar set of

recommendations as those of Qureshi, which, again, can be boiled down to "make the product modular and make the product flexible."

- *Increase the degree of modularity of a device*
- *Reduce the number of parts requiring manufacturing changes*
- *Reduce the communication between modules, and enable the device to function normally regardless of the orientation, location and arrangement of its individual modules*
- *Facilitate the addition of new functionality and rearrangement or scaling of parts*
- *Enable the device to respond to minor changes*

Aside from the lack of novelty in the recommendations for both of these studies, the obvious concern is whether the screening criteria for identifying flexible products were valid. For all of the data in Qureshi's method, as well as half of the data in Keese's approach, candidate flexible products were identified via a database search (i.e., the U.S. patent database). This search entailed criteria like, "references to other evolutions, multiple preferred embodiments, and direct references to design flexibility in their text." It's not apparent that these search terms would yield truly flexible products. In terms of Keese's adjunct product listing, since it relied on CMEA, the same concerns raised previously regarding its validity would apply.

Rajan [2005] also used empirical data to evaluate product flexibility, and also employed CMEA. As part of his findings, Rajan provides guidelines in order to aid in designing flexibility. In Rajan [2003], he offered the following recommendations to achieve flexibility:

- *Improve the design flexibility by making the device more modular*
- *Reduce the effect of a change in a design by increasing the number of partitions*
- *Reduce the effect of a change by increasing the number or size of buffer zones*
- *Reduce the occurrence of changes by standardizing components and interfaces*
- *Reduce the occurrence of a change by increasing the performance envelope*
- *Reduce occurrence of changes by selecting technology which is far from obsolescence*

The first four recommendations are related to modularity. The fifth is more about versatility than flexibility. And the last may be a reasonable systems engineering heuristic under certain conditions (e.g., when mission life duration is a priority), but it doesn't seem to directly allow for more flexibility. If anything, the direction of causality would seem to flow the other way, i.e., a more flexible design will lead to the use of technologies further from obsolescence.

In Rajan [2005], he amplifies on these recommendations in the form of several additional guidelines:

- *Modularizing the design leads to more product flexibility. As the design becomes more integrated, it becomes more inflexible for redesign.*
- *"Designing the modules in a product, as external attachments, makes the design even more flexible.*
- *Designing with more standard components and interfaces will improve product flexibility.*
- *Directed partitioning of a design into a greater number of elements (manifested through higher numbers of components and functions) improves the flexibility.*
- *Reducing the number of parts within modules, after effective layout, does not affect flexibility (this insight must be verified in future studies). The implication is to have simultaneous design for improved assemblability, while maintaining flexibility"*

Aside from our perfectly justifiable desire to throttle Rajan for introducing the most ridiculous "–ility" yet (i.e., "assemblability"), we find that the result is again just a list of heuristics to achieve modularity. Rajan could have made his point more succinctly by simply saying, "If you want to implement flexibility, make sure you implement modularity."

<u>Design For Adaptability</u>

Another approach to implement flexibility is through a method known as *Design for Adaptability*, or DFAD. While certain articles on DFAD neglect to define what they mean by adaptability [Lipson, 2001], it is apparent from context that the principle involved is close enough to flexibility to be of potential interest to us. The driving principle of DFAD is to design the product so that it can have a longer useful life. From Kasarda [2007]—

"The DFAD methodology concept is based on the hypothesis that product life ends because a product is unable to adapt to change. A product may be retired for myriad reasons including that it is broken, out of style, or has become inefficient due to technology obsolescence. In these cases, the product was not able to adapt to change—it was unable to self-heal, it could not modify or reconfigure to meet changing fashion needs, or it could not be upgraded, for physical or economic reasons, to utilize new technology. To address these and similar issues, we are developing the DFAD methodology."

DFAD is described as being similar to the Darwinian process of evolution and adaptation [Kasarda, 2007]. More formally, it is rooted in control theory in that products are modeled as dynamic systems with feedback control mechanisms for adapting to "changes in product performance criteria" in order to achieve a longer useful life [Kasarda, 2007;Lipson, 2001].

Unfortunately, little else can be said regarding DFAD. The research stream appears to have withered, as there are few publications that refer to it, and the actual usable content in the publications is sparse. Without more details on its application, DFAD does not appear to be a viable implementation strategy.

Design For Changeability

Schulz [1999] creates a method to implement flexibility that he calls *Design for Changeability* (DFC). DFC is comprised of four strategic attributes: flexibility, agility, robustness, and adaptability. Schulz refers to systems as "intelligent" if they consist of all four attributes. He then introduced terminology related to "Basic Principles" and "Extending Principles." The Basic Principles support all four attributes and consist of Ideality/Simplicity, Independence, and Modularity, Encapsulation (which he defines via DSMs). The extending principles have more restrictive application (i.e., don't apply to all four strategic attributes), and include a number of principles such as Integrability, Autonomy, Scalability, Decentralization, Redundancy, and Reliability.

Unfortunately, the author's discussion ends abruptly with this outline of design principles, without any case study examples or discussion of how to use these principles effectively to achieve genuine changeability in practice. This is a key step as the principles, as delineated by Schulz, are compelling, but rather abstract. The author recognizes these shortcomings and states that he plans to address them in future research; however, that did not appear to happen as the DFC concept has not appeared in the literature subsequently.

Acquisition Strategy

Presumably, we can cultivate flexibility in the design process to some degree via the specific acquisition strategies we choose to employ. For instance, consider the contract type. If we elect to use a firm-fixed price contract, we gain (in theory) a guaranteed capability at a guaranteed price. However, we sacrifice the ability to quickly respond to new information or priorities that may emerge as we progress through the program as we might do under a level-of-effort (i.e., cost-plus) contract. This is also why it is not a good idea, in general, to procure a system using a firm fixed price contract if there is sizeable uncertainty. The contract type is one element of our acquisition strategy that is likely to have a bearing on our ability to develop a flexible system.

Although there does not appear to be any research on how system flexibility relates to contract type, there is some discussion in the literature regarding how another aspect of acquisition strategy may foster flexibility. Recall that in a previous section, we noted that flexibility only had value under conditions of uncertainty, and touched on the fact that keeping options open as long as possible was a method of mitigating the impacts of uncertainty. Delaying commitment (and thus remaining flexible longer) can also be accomplished via certain procurement strategies, namely *incremental* development and *iterative* development. Mikkonen [2001], in discussing software flexibility, describes

incremental development as a technique to "leave some parts of the architecture open," and "provide stub functions for unimplemented features," the exact capabilities that we're looking for with design flexibility.

Iterative development provides flexibility in a similar manner, as design commitments occur in steps thereby allowing for the accrual of time and knowledge to provide more flexibility with respect to design decisions: "Iterative development requires accepting the fact that requirements cannot always be adequately specified without studying systems iteratively," and that rapid incremental prototyping is essential to obtaining new system insights and improved implementations [Mikkonen, 2001]. Along these lines, some have suggested that prototyping a system is actually superior, in most cases, to the practice of specifying. According to Boehm [1984], prototyping allows "changes late in the design process as a result of new information from customers resulted in products that were not only judged superior from a customer perspective but also developed with fewer design resources."

According to some, another acquisition strategy for achieving flexibility is to simply provide for *reserve margins* in all performance areas where changes are deemed more likely to impact the system design [Eckert, 2004; Krishnan, 2002]. Note that this is somewhat distinct from the over-capacitization approach discussed earlier when distinguishing flexibility from versatility. Now, we are referring to *over-designing* the system so that perturbations are less likely to result in a reduction of performance below a required threshold. What this would mean in practice is investing in a design approach that could seamlessly accommodate (vice allow for modification, under the stricter view of flexibility) various uncertain alternatives. The hope is that the investment is worthwhile, as the "potentially expensive redundancy is designed into the product, making future redesign much cheaper" [Eckert, 2004]. Note, however, that at the moment that the reserve margin is implemented, uncertainty (for that parameter) disappears, and flexibility is no longer germane.

Krishnan [2002] presents a related strategy to achieve the same effect. By committing to one or more "parallel project paths," the program has more flexibility to contend with multiple source of uncertainty. Note, however, that this strategy is only applicable to foreseeable-type changes. It should also be evident that this discussion is closely related to basic principles of risk management, and serves to elucidate the intricate relationships among flexibility, uncertainty, risk, and opportunity.

In broader program management terms, design flexibility may also encompass, "capability restoration, capability augmentation, risk diversification, schedule diversification, or uncoupling of system requirements" [Brown, 2007]. Ross [2008] calls for acquisition policy changes that would allow unused change mechanisms to be tracked and managed at lower levels, similar to the concept of management reserve, and thus could be thought of as "change reserve." Ross references Boeing's development of the JDAM, and notes that this type of approach was employed successfully. By allowing the contractor to maintain ownership of the design, it "facilitated the changing of the

design over time with less 'cost.'" Given the authority to manage the change reserve, Boeing's design was highly modular, COTS-intensive, and consisted of interfaces with excess capacity.

Other Strategies

We will close this chapter on implementing flexibility with a quick look at some other methods discussed in the literature that, while interesting, are not substantive enough to warrant detailed consideration.

According to Willems, et al. [2003], quantifying a product's adaptability can be achieved through a process they have named Methodology for Assessing the Adaptability of Products (MAAP). This process purportedly supports the identification of improvement potential in the design of the product, and its components, though the applicability requires that the types of changes that must be adapted to be known a priori. The methodology is validated via a case study involving cellular phones.

The principle of open architecture is another possible approach to achieving flexibility. Increasingly effective in the software domain, the idea has been suggested that this type of architectural approach could be extended to hardware [Piller, 2010]. The idea is that "embedded toolkits" could be provided to designers, allowing them to "design products with build-in [sic] flexibility by embedding knowledge and rules about possible product differentiations into the product." This is a very recent article, and the concept is not yet mature; at this time, the authors are looking for a "proof of concept" opportunity.

Summary

"It is not possible to know exactly how a particular design will perform until it is built. But the product cannot be built until the design is selected. Thus, design is always a matter of decision making under conditions of uncertainty and risk" [Hazelrigg, 1998].

Hazelrigg's observation goes to the heart of the problem in implementing flexibility. We know that it is incumbent upon the procuring agency, not the user, to infuse flexibility into the system. This is undoubtedly a challenging endeavor as the literature is littered with many porous attempts. As Hazelrigg observed over a decade ago when referring to coeval design approaches: "these methods are *ad hoc* approaches that are not rooted in any fundamental theory, nor do they provide a basis for engineering design as a discipline." Unfortunately, it appears that little has changed since then. Based on what we can glean from the literature, perhaps the only lesson is that if we can implement modularity, then we have gone a long way in implementing flexibility. Though, even for this, the evidence is more anecdotal than analytical.

Appendix B: Case studies

B.1: SHIPMAIN Case Study

Data Collection: Aggregate data was gathered during an initial KVA knowledge audit conducted via survey and a group interview setting at NAVSEA, Washington Navy Yard, DC. Three SHIPMAIN SMEs were present at the group interview, and each had expertise related to the SHIPMAIN process. The three SMEs each have over 30 years experience in the shipyard industry, with a high degree of expertise in their affiliated disciplines. Their input will be statistically analyzed for reliability, and all estimates will be aggregated to reflect the cost and number of process executions averaged over five years. Business rules for Phases IV and V of the SHIPMAIN process guided the interview.

Phases IV and V of the SHIPMAIN process were created from input and discussion by various stakeholders at NAVSEA, Type Commanders (TYCOM), public and private shipyards, Space and Naval Warfare Systems Command (SPAWAR), Office of the Chief of Naval Operations (OPNAV) and other entities with a vested interest in maintenance and modernization efforts (Commander, Naval Sea Systems Command, 2006). Business rules for these phases are regularly reviewed and updated to be properly aligned with business goals and the needs of Fleet Commanders. Currently, Phases IV and V of SHIPMAIN are not in a functionally implemented state but are rather in an early adoption period while business rules/processes mature and long-standing legacy practices give way to the SHIPMAIN process. A key assumption of this proof-of-concept case is that the SHIPMAIN process functions as described in the business rules listed in Appendix D of the SSCEPM dated December 11, 2006.

Methodology: The method of analysis for this proof of concept is the Learning Time method.[3] A thorough discussion and review of current SHIPMAIN business rules with the SMEs established what processes constitute the core of SHIPMAIN Phases IV and V, identified the inputs and outputs of those processes, and determined the frequency of core process iterations. The discussion further established boundaries between the defined processes in order to effectively apply the KVA methodology and to properly identify and valuate the knowledge required for each. Eight core processes were identified, and detailed descriptions of each were provided by the SMEs and the SHIPMAIN business rules. Each core process requires a certain level of knowledge in one or more of the following areas: administration, management, scheduling, budgeting, basic computer skills, engineering, shipboard systems, logistics or project management.

[3] See Appendix A for a detailed discussion of Learning Time.

The SMEs spent considerable time contemplating the amount of knowledge embedded in each core process, and provided ALT estimates for each. The established baseline level of knowledge for consideration was a GS-13 employee with 1 year of experience and a college degree (no field specified). Finally, the team of SMEs provided individual and uninfluenced RLT and rank-order estimates, which lead to a correlation of greater than 80 percent—thereby establishing a high level of reliability on the ALT figures obtained. Additional discussion occurred spontaneously among the SMEs, which lead to a group conclusion that Blocks 265 and 300 were equivalent in complexity. Adjusting the RLT and rank order to reflect that conclusion leads to greater than a 90-percent correlation across the data fields.

Key Assumptions: As previously mentioned, this analysis is based on information collected from previous research by LT Christine Komoroski (2005), SMEs from NAVSEA, data contained in the NDE and current directives. For the purposes of this study, all maintenance and modernization efforts are assumed to occur as described in the current business rules listed in Appendix D of the SSCEPM dated December 11, 2006. It is also important to keep in mind that maintenance and modernization efforts vary substantially in number, manpower requirements, duration and complexity. After conducting extensive interviews with SMEs and conducting a thorough review of current directives, related research and existing data in the NDE, the researchers made the following assumptions:

- Of 1,200 annual modernization and maintenance availability periods, 25 percent involve low complexity installations, 25 percent high complexity installations, and 50 percent involve medium complexity installations. Assume all efforts in this study involve efforts of medium complexity.
- On average, 20 SCDs are generated per week.
- The market comparable labor rate is 35 percent greater than the government labor rate.
- Price per common unit of output is $75.45.

Discussion of As-is Scenario

Number of Employees. The number of employees value used to build this model represents the number of employees assigned to complete the given process for each cycle or iteration. Numbers assigned are based on interviews with SMEs. By accounting for the number of personnel involved in each process, the researchers can determine how often knowledge is used. This method also provides an approximate way to weight the cost of using knowledge in each process.

Times Performed in a Year. Estimations for the number of times each process is executed per year are based on the aggregated number of occurrences for each process. The NDE was queried with the following filters to gather the raw data:

The search was limited to title "K" and "P" alterations.

- FY 2002 through 2007.
- Ships of the following TYCOMs:
    - Commander, Naval Air Force Atlantic
    - Commander, Naval Air Force Pacific
    - Commander, Naval Surface Force Atlantic
    - Commander, Naval Surface Force Pacific

These filters were put in place to establish a five-year average of maintenance or modernization availability periods for all surface combatant ships to include Aircraft Carriers. The result of the query was that an average of 1,200 availability periods occur each year. This number was conditionally modified to take the complexity of installs during availability periods into consideration. To provide a reasonable scope, 25 percent of availability periods were considered to be simple, 25 percent complex and 50 percent moderate. 600 moderately complex installations frame the scope of this model.

The number of times the process is performed for the remaining blocks is based on the number of installations that occur. For each installation that occurs, a SCD is generated, and the number of SCDs provides a reliable proxy for the number of installations. SMEs provided data and analysis which estimates an average of 20 SCDs are initiated per week, leading to 1,040 SCDs generated annually. Applying the same conditional modifier to account for complexity, 520 SCDs or installs, would occur each year.

*Actual Learning Time***.** In order to determine the ALT from a common point of reference, the SMEs were instructed to imagine a baseline individual of a college graduate at the GS-13 civilian rank level with a year of experience in some sector of the shipyard industry. All experts understood that each process learning time estimate must adhere to the basic assumptions that knowledge is only counted if in use, and the most succinct path to achieve a unit of output must be considered. Each core process was broken down into its component sub-processes, and respective ALT values were assigned for each sub-process. The final ALT value for each core process is a summation of the sub-process ALT estimates. Finally, all ALT values are based on the following time assumptions:

- One year = 230 work days
- One month = 20 work days
- One week = 5 work days
- One day = 8 hours

Determining Value. Each process contains a certain amount of process automation—ranging from zero to 100 percent. The amount of automation is a proxy for how much knowledge is embedded in the IT supporting the automation. It is important to estimate how much of each process is automated, and to be consistent in those estimates, so that the knowledge embedded in the technology resources is accounted for. Upon

determination of the percentage estimate, the Total Learning Time (TLT) is calculated by dividing ALT by the percentage of process automation for that process.

The TLT value is then multiplied by the number of employees and the number of times the process is performed per year to establish a Total Knowledge factor. The Total Knowledge factor is then multiplied by a price per common unit, based on market comparables, to derive the "benefits" or "value" of each process. The resulting product is then used as the numerator for determining ROK and ROI.

Cost-estimation. To estimate the cost of government employees involved in the processes, the 2007 civilian pay chart was referenced. Each civilian pay grade has associated "steps" to account for various unique factors of each job. All pay estimates are based on Step Six of the associated pay grade. Since the processes take place across the globe, no locality pay differentials were taken into consideration to minimize variation. Also, because basic computing hardware and software is utilized in every scenario, IT cost is not included in the As-is analysis. It is assumed that each employee in this process has an email account, laptop or desktop computer with identical software and has access to a printer. Material, travel, and other miscellaneous costs are not included in this analysis so labor cost may be isolated.

Establishing a market comparable for government labor was accomplished by comparing the pay of contractors who conduct the same type and scope of work as the government employee. The contracted base pay was on average 35 percent higher than the government employees. Benefits, locality pay differential and other variables were not compared to establish this rate; only base pay was considered. All government employee rates were increased by 35 percent to achieve the values for the market price used to establish a price per common unit of output.

Block As-is KVA Data

Block 265
Hull Installation and Risk Assessment

	Sub process	Hourly Personnel Cost	Head count	Times Perf. Per Year	Time to Complete (Hrs)	Annual Personnel Cost	%IT	ALT (Hrs)	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
265.1	Installation Procurement, Design & Advance Planning	$43.10	35	520	160	$125,507,200	25%	40	970667	$72,071,847	$125,507,200	57%	-43%
265.2	Hull Installation Readiness Review	$29.78	2	520	40	$1,238,848	80%	40	208000	$15,443,967	$1,238,848	1247%	1147%
265.3	Evaluate Maturity Status	$50.16	1	520	20	$521,664	0%	40	20800	$1,544,397	$521,664	296%	196%
265.4	Provide Risk Assessment	$50.16	1	520	40	$1,043,328	0%	56	29120	$2,162,155	$1,043,328	207%	107%
265.4.1	Formally Propose Install for Readniess Assessment and Auth.	$50.16	1	520	20	$521,664	0%	40	20800	$1,544,397	$521,664	296%	196%
265.5	Risk/Readiness Determination	$59.01	4	130	40	$1,227,408	0%	56	29120	$2,162,155	$1,227,408	176%	76%
									Process Totals:	**$94,928,918**	**$130,060,112**	**73%**	**-27%**

Block 270
Authorize Installation

	Sub process	Hourly Personnel Cost	Head count	Times Perf. Per Year	Time to Complete (Hrs)	Annual Personnel Cost	%IT	ALT (Hrs)	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
270	Installation decision	$76.00	4	520	20	$3,161,600	85%	24	332800	**$24,710,347**	**$3,161,600**	**782%**	**682%**

Block 280
Resolve "Not Authorized/Deferred SC"

	Sub process	Hourly Personnel Cost	Head count	Times Perf. Per Year	Time to Complete (Hrs)	Annual Personnel Cost	%IT	ALT (Hrs)	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
280	Update HMP,LOA and Fielding Plan	$29.78	1	520	40	$619,424	75%	24	49920	$3,706,552	$619,424	598%	498%

Block 300
Install SC

	Sub process	Hourly Personnel Cost	Head count	Times Perf. Per Year	Time to Complete (Hrs)	Annual Personnel Cost	%IT	ALT (Hrs)	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
300	Complete installation and testing	$42.45	46	520	40	$40,616,160	25%	40	1275733	$94,722,998	$40,616,160	233%	133%

Block 310
Feedback: Cost, CM, Performance, Schedule, ILS

	Sub process	Hourly Personnel Cost	Head count	Times Perf. Per Year	Time to Complete (Hrs)	Annual Personnel Cost	%IT	ALT (Hrs)	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
310	Provide Feedback Data	$29.78	2	520	20	$619,424	0%	24	24960	$1,853,276	$619,424	299%	199%

Block 320
Continue Installs

	Sub process	Hourly Personnel Cost	Head count	Times Perf. Per Year	Time to Complete (Hrs)	Annual Personnel Cost	%IT	ALT (Hrs)	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
320	Determine impact on future installs from Feedback in 310	$59.01	5	520	20	$3,068,520	0%	24	62400	$4,633,190	$3,068,520	151%	51%

Block 330
Final Install, Closeout SC

	Sub process	Hourly Personnel Cost	Head count	Times Perf. Per Year	Time to Complete (Hrs)	Annual Personnel Cost	%IT	ALT (Hrs)	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
330	Verify all SCs have been completed	$29.78	1	520	20	$309,712	0%	24	12480	$926,638	$309,712	299%	199%

Table 14: To-be Process Analysis

This scenario represents a combination of notional and verified data to portray current activities contained in the SHIPMAIN process reengineered to maximize utilization of 3D laser scanning and PLM assets. Not every sub-process will be affected in this scenario; instead, only affected processes will be used for comparison. All others may be assumed static as described in their as-is state.

Cost of 3D Terrestrial Laser Scanning Technology

The cost for laser scanning equipment and required software was provided by the IEDP Project Manager for SIS. The SISs IEDP Project Manager stated that the current cost has not changed from the estimates LT Komoroski used in her 2005 research (B. Tiltion, personal communication, May 16, 2007). For this study, the cost for IT used in LT Komoroski's 2005 study will be increased by 3% to account for inflation and will be amortized over a 10-year period. Cost and assumptions for the 3DIS are:

- Current inflation adjusted initial cost is $90,640 for one 3DIS scanner and its applicable software suite.
- Maintenance/upkeep annual cost-estimate is 20 percent.
- Use estimate is 200 days per year.
- Lifespan estimate is 10 years.
- The resulting cost per unit per day is: $135.96.

- For analysis of the to-be KVA model, this cost is absorbed by the actual scanning process contained in Block 265.1.

The six planning yards that support naval surface force assets are: Bath Iron Works, Bath, ME; Norfolk Naval Shipyard, Norfolk, VA; Northrop Grumman Ship Systems, Avondale OP, New Orleans, LA; Northrop Grumman Ship Systems, Ingalls OP, Pascagoula, MS; Puget Sound (DET) Boston, Boston, MA and; Puget Sound Naval Shipyard, Bremerton, WA (NAVSEA Shipbuilding Support Office, 2007).

To properly account for the enterprise-wide cost of the 3DIS product, the daily cost was increased by a factor of 6 under the assumption that each planning yard received one scanner with the required software. Accordingly, the daily cost to introduce 3DIS across the enterprise would be $815.76.

Cost of PLM Technology

SIS is a Value-added Reseller of UGSs PLM suite of software called Teamcenter. Under the IEDP, Teamcenter products will be introduced to establish an Integrated Data Environment using team collaboration and configuration data-management platforms. The Teamcenter suite contains the following specific product solutions: Community Collaboration; Compliance Management; Engineering Process Management; Enterprise Knowledge Management; Lifecycle Visualization; Maintenance, Repair and Overhaul; Manufacturing Process Management; Portfolio and Program Management; Reporting and Analytics; Simulation Process Management; Supplier Relationship Management, and Systems Engineering (UGS Corporation, 2007).

For the scope of this study, Community Collaboration, Engineering Process Management, Lifecycle Visualization, Portfolio and Program Management, Reporting and Analytics and the Supplier Relationship Management solutions will be considered. These solutions will be part of the complete PLM solution evaluated in the to-be model. Cost estimation for these tools has proven to be difficult. According to a leading PLM provider, "Identifying an accurate, average or generalized pricing schema for respective toolsets within the PLM space is almost unachievable. It is safe to say, however, that vendor's price-models have been decreasing over the years" (Anonymous, personal communication, June 2007).

To establish a reasonable cost for the Teamcenter solution, the following cost estimation will be used:

- An assumption that PLM and Enterprise Resource Planning (ERP) initiatives are similar in cost and scope.
- DoD spent an average of $250 million per ERP initiative in FY 06 (Service Cost Estimating Organizations, 2007).
- The Department of the Navy (DoN) budget for FY 06 was $122.9 billion, including supplemental transfers (Bozin, 2006)

- DoN budget for Ship Depot Maintenance was $3.72 billion, or 3 percent of the entire DoN budget (Bozin, 2006).
- 3 percent of a $250 million (the cost for an ERP) is $7.5 million.

The $7.5 million PLM solution will be deployed at the six planning yards listed earlier in this section and at all SYSCOMs/TYCOMs supporting surface force combatant assets. The cost for the PLM suite will be amortized over 10 years with a 2 percent annual increase for the cost of version upgrades—bringing the total cost to $9 million. It is assumed that the PLM software will be used 230 days per year, making the daily cost of PLM software $3,913. This cost will be distributed equally across all processes of Phases IV and V of SHIPMAIN.

To-be Block Assumptions and Data Analysis

Reengineering the to-be scenario proved to be quite challenging. While the formal guidance for SHIPMAIN is relatively mature for Phases I-III, that is not so for Phases IV and V. Remarkable effort has been put into developing and refining the business rules associated with Phases IV and V, and they continue to be in a maturing phase at the time of this study. According to one SME, until all areas become aligned with the business rules and until the required technology to support them is acquired, the processes currently in use to accomplish the tasks in Phases IV and V are the legacy procedures. As the business rules, governance structure and core technologies mature, the processes as defined in current SHIPMAIN business rules should become the standard practice. In order to model the notional to-be scenario, strict observation of currently defined business rules were coupled with SME assessments of their practical implementation for each core process. For additional clarity, all core processes will be described in terms of their sub-processes and the assumptions affecting key parameter changes from the as-is to the to-be scenario.

Block 250 Authorize and Issue Letter of Authorization (LOA)/Hull Maintenance Plan (HMP); Generate 2Ks														
	Sub process	Hourly Personnel Cost	Head count	Times Perf. Per Year	Time to Complete (Hrs)	Annual Personnel Cost	IT Cost	%IT	ALT (Hrs)	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
250.1	Create AHMP/EHMP	$42.45	0	720	1	$0	$56,250	100%	40	28800	$2,138,395	$56,250	3802%	3702%
250.2	Create Annual HMP/LOA	$42.45	1	1200	40	$2,037,678	$56,250	75%	32	153600	$11,404,776	$2,093,928	545%	445%
250.3	Initiate 2Ks into ICMP	$35.70	1	624	1	$22,276	$56,250	99%	32	19968	$1,482,621	$78,526	1888%	1788%
250.x	Generate/issue QISM	$42.45	2	4	8	$2,717	$56,250	90%	32	2560	$190,080	$58,967	322%	222%
									Process Totals:		**$15,215,872**	**$2,287,671**	**665%**	**565%**

Table 15: Block 250 (ROK)

Assumptions for Block 250 are:

- PLM product suite would provide the means for processes identified in the business rules as "future enhancements" to become a reality.
- A conservative estimate of 20 percent greater efficiency was applied to the times fired per year for Blocks 250.1 and 205.3 due to automation.

Block 265 Hull Installation and Risk Assessment														
	Sub process	Hourly Personnel Cost	Head count	Times Perf. Per Year	Time to Complete (Hrs)	Annual Personnel Cost	IT Cost	%IT	ALT (Hrs)	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
265.1	Installation Procurement, Design & Advance Planning	$43.10	17	624	128	$58,527,196	$219,402	75%	40	1697280	$126,022,772	$58,746,598	215%	115%
265.2	Hull Installation Readiness Review	$29.78	2	520	32	$991,238	$56,250	85%	40	277333	$20,591,956	$1,047,488	1966%	1866%
265.3	Evaluate Maturity Status	$50.16	1	520	20	$521,696	$56,250	0%	40	20800	$1,544,397	$577,946	267%	167%
265.4	Provide Risk Assessment	$50.16	1	520	40	$1,043,391	$56,250	0%	56	29120	$2,162,155	$1,099,641	197%	97%
265.4.1	Formally Propose Install for Readniess Assessment and Auth.	$50.16	1	520	20	$626,035	$56,250	0%	40	124800	$9,266,380	$682,285	1358%	1258%
265.5	Risk/Readiness Determination	$59.01	4	130	40	$1,227,347	$56,250	0%	56	29120	$2,162,155	$1,283,597	168%	68%
										Process Totals:	**$161,749,816**	**$63,437,554**	**255%**	**155%**

Table 16: Block 265 (ROK)

Assumptions for Block 265 are:

- There are 17 unique tasks involved in Block 265.1.
- The 15 employees required for the ship-check task of Block 265.1 don't use the entire time allotted to complete the process. The 15 ship check employees are notionally reallocated to remaining tasks of a similar pay grade.
- Two additional employees are required to accomplish the 17 tasks.
- Cycle-time will improve by a conservative estimate of 20 percent with the addition of PLM and 3D laser scanning. PLM will allow suppliers and purchasers to share requirements and plan for delivery in a real-time, Integrated Data Environment. 3D laser scanning will provide more accurate design parameters to suppliers than hand-drawn images—reducing the amount of "field engineering" required.

Block 280 Resolve "Not Authorized/Deferred SC"														
	Sub process	Hourly Personnel Cost	Head count	Times Perf. Per Year	Time to Complete (Hrs)	Annual Personnel Cost	IT Cost	%IT	ALT (Hrs)	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
280	Update HMP,LOA and Fielding Plan	$29.78	1	520	24	$371,714	$56,250	80%	24	49920	**$3,706,552**	**$427,964**	**866%**	**766%**

Block 300 Install SC														
	Sub process	Hourly Personnel Cost	Head count	Times Perf. Per Year	Time to Complete (Hrs)	Annual Personnel Cost	IT Cost	%IT	ALT (Hrs)	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
300	Complete installation and testing	$42.45	36	624	35	$33,377,170	$56,250	35%	40	1275733	**$94,722,998**	**$33,433,420**	**283%**	**183%**

Table 17: Block 280 and 300 (ROK)

Assumptions for Block 300 are:

- The majority of management and verification tasks will be accomplished by 30 percent fewer staff due to collaboration and access to the common data environment provided by PLM.
- Cycle-time will improve by 20 percent due to:
- Improved coordination between suppliers and the shipyards
- Less rework due to installation items being built more accurately from the 3D imagery provided of as-built configuration.

Block 310 Feedback: Cost, CM, Performance, Schedule, ILS															
	Sub process	Hourly Personnel Cost	Head count	Times Perf. Per Year	Time to Complete (Hrs)	Annual Personnel Cost	IT Cost	%IT	ALT (Hrs)	Total Knowledge	Total Benefits	Annual Cost	ROK	ROI
310	Provide Feedback Data	$29.78	1	624	10	$185,857	$56,250	50%	24	24960	$1,853,276	$242,107	765%	665%

Table 18: Block 310 (ROK)

Assumptions for Block 310 are:

- PLM will enable a 50 percent reduction in staff by having all related information available through a single interface.
- Time to complete the tasks will be reduced by 75 percent by eliminating lengthy manual data collection and aggregation.
- The process will be executed 20 percent more often annually.

B.2: CCOPS Case Study

USS Readiness Case Study

The KVA valuation framework was applied to the fictitious U.S. Navy warship, USS Readiness. Our case study focused on the cryptologic carry-on program (CCOP) portfolio of intelligence information systems and in particular, the ship borne signals intelligence collection process. KVA+RO allows for analysis of existing and future CCOP systems on ISR activities, processes and operations for each system in the portfolio. Individual CCOP systems in the portfolio can be compared once baseline data is created, enabling decision-makers to make financial decisions and projections based on quantitative data.

Case Study Background

The USS Readiness is outfitted to conduct Intelligence, Surveillance, and Reconnaissance (ISR) missions and has a contingent of information warfare operators performing intelligence collection processes utilizing CCOP systems. Principal sub-processes in the ICP are shown in the following diagram.

The warship is equipped with four CCOP systems (A, B, C, and D). CCOP systems may be used in a single sub-process or across sub-processes, and some systems such as CCOP A are highly complex with multiple subsystems. Each sub-process is further broken down into individual actions that may be required to perform the sub-process in the intelligence collection process. For example, sub-process "Target Data Processing" can be broken down into a number of human-based tasks requiring no automation.

Applying KVA Methodology

KVA methodology was applied to quantify the value added by CCOP systems, information warfare/cryptologic operators, and the enabling ship borne system infrastructure with which they interact. Value provided by human capital elements were compared to IT elements to measure efficiency (productivity) and effectiveness (profitability). All assets, sub-processes, and outputs are first identified.

- ***Asset*** analysis encompasses all value and cost data related to each asset in the process, human capital or IT asset.
- ***Sub-process*** analysis includes a detailed breakdown of the ICP to include the time-to-learn, how to perform each sub-process, and number of executions for each sub-process.
- ***Process*** outputs are established via time to learn estimates, including the total number of aggregated process outputs and a surrogate revenue stream used to monetize the outputs.

Asset values and costs are then allocated throughout the sub-processes in which they contribute to the production of outputs. The time-to-learn (knowledge embedded in each sub-process) is multiplied by the number of executions of that sub-process, and the figure serves as a basis for revenue allocation at the sub-process level. Costs are calculated by multiplying the time it takes to produce the process output times the salary of those producing it and the cost per usage of the IT asset. Costing typically does not include the cost of fixed assets as these costs are typically used as a constant weighting factor. Therefore, these costs usually do not affect the relative performance estimates for the various sub-processes.

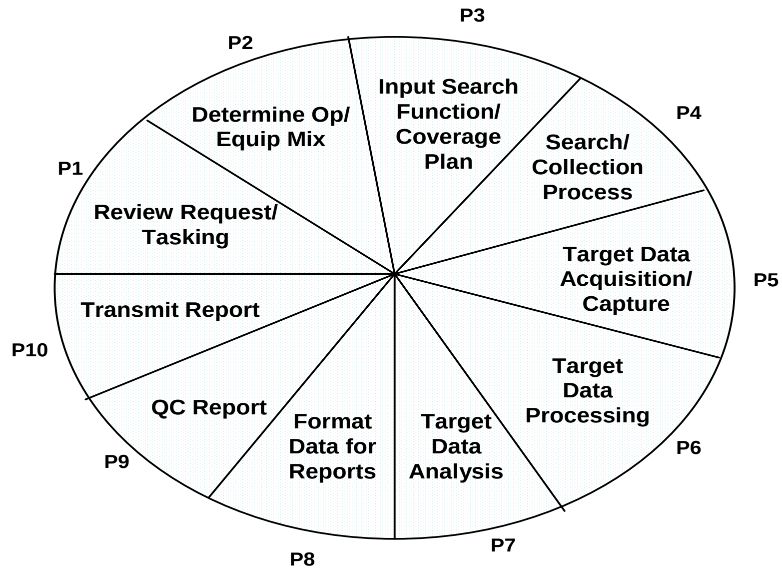


Figure 23: The Intelligence Collection Process

	SUB-PROCESS NAME	CCOP A	CCOP B	CCOP C	CCOP D
P1	Review Request/Tasking	X			
P2	Determine Op/Equip Mix	X			
P3	Input Search Function/Coverage Plan	X			
P4	Search/Collection Process	X	X		
P5	Target Data Acquisition/Capture	X	X		
P6	Target Data Processing	X	X	X	X
P7	Target Data Analysis	X		X	X
P8	Format Data for Report Generation	X			
P9	QC Report	X			
P10	Transmit Report	X			

Table 19: USS READINESS CCOP Systems

Performance ratios such as ROKA and ROKI can be calculated after costs and benefits for each sub-process are defined.

Case Study: KVA Results

KVA analysis was used to compare two example sub-processes: "Search and Collect" (P4) and "Format Data for Report Generation" (P8). Results are summarized in the following tables and issues were identified at the portfolio, program and process levels.

Sub-Process		CCOP A	CCOP B	CCOP C	CCOP D	ROK
Review Request/Tasking	P1	168.54%				168.54%
Determine Op/Equip Mix	P2	166.86%				166.86%
Input Search Function/Coverage Plan	P3	152.91%				152.91%
Search/Collection Process	P4	930.03%	148.15%			590.13%
Target Data Acquisition/Capture	P5	290.15%	147.71%			228.23%
Target Data Processing	P6	319.39%	162.59%	436.13%	28.18%	142.41%
Target Data Analysis	P7	149.98%		534.76%	34.55%	121.42%
Format Data for Report Generation	P8	143.34%				143.34%
QC Report	P9	315.88%				315.88%
Transmit Report	P10	148.75%				148.75%
ROK for Total Process		278.59%	152.81%	485.44%	31.37%	196.27%

Table 20: Return on Knowledge (ROK) USS READINESS Summary KVA Results

CCOP D is a cost-heavy system that executes very few times with negative ROKs throughout the sample period, as seen in Table 20.

- Is CCOP D appropriate for this platform and mission?
- What is a less expensive alternative to CCOP D?
- Are all operators appropriately trained in the use of CCOP D?

The Search and Collect process (P4) is knowledge-intensive requiring IT and human capital asset investments to complete, as indicated in Table 21. Moreover, each process output necessitates many executions of the sub-process.

- Could an even higher return be achieved with further automated search and collection systems or more operators?
- Should the amount of knowledge in humans and IT be adjusted?
- Could a broader range of training allow operators to perform more functions?

The Search and Collect process (P4) is a high performer with an overall return of 239% compared to a -20.37% return for the Format Data for Report Generation process (P 8).

- What accounts for the discrepancy in the returns received on each process?

The Format Data for Report Generation process (P 8) only executes once per intelligence report (process output) with nearly one third of all operators assigned to this sub-process one fifth of the total human cost.

- What causes this low efficiency level?

The Format Data for Report Generation process (P 8) is more automated than P4.

- Could this process be further automated or performed by other operators to yield higher efficiency **and** effectiveness levels?

Sub-Process		**CCOP A**	**CCOP B**	**CCOP C**	**CCOP D**	**ROKI**
Review Request/Tasking	P1	68.54				22.11
Determine Op/Equip Mix	P2	66.86				20.89
Input Search Function/Coverage Plan	P3	52.91				-18.44
Search/Collection Process	P4	830.03	48.15			*239.01*
Target Data Acquisition/Capture	P5	190.15	47.71			47.28
Target Data Processing	P6	219.39	62.59	336.13	-71.82	36.67
Target Data Analysis	P7	49.98		434.76	-65.45	21.25

Format Data for Report Generation	P8	43.34				*-20.37*
QC Report	P9	215.88				79.19
Transmit Report	P10	48.75				-17.37
Metrics for Aggregated		178.59	52.81	385.44	68.63	109.9

Table 21: Return on Knowledge Investment (ROKI) USS READINESS Summary KVA Results

Answers to these questions could help program managers allocate funds to new systems or to existing systems for improve products or to eliminate a system from the CCOP portfolio. Results could also be used to tailor manning and training requirements of ISR crews deploying CCOP systems.[4]

Real Options Analysis

Real options analysis was performed to determine the prospective value of three basic options over a three-year period using KVA data as input for the analysts. Three potential scenarios were identified.

Results of the real options analysis indicate that Option C delivers the highest value at $15.2 million. Although apriori, Options A and B were expected to have significant cost savings, it is possible to see greater total value, with much lower volatility (risk), for Option C with RO analysis. Fleet and Ship Commanders who intuitively preferred Option C because it permitted greater control of intelligence assets for specific operations, now have objective data to help them review their preferred option. This is not to say that the other options might provide greater strategic value in the long run once they are implemented with more productive CCOPs assets and lower volatility based on overcoming the initial decrements in the learning curve of a new process implementation.

[4] This case study revealed a few limitations to implementation of KVA to the Intelligence Collection Process as modeled in for the USS READINESS. Please see Appendix 2 of the complete case study for limitations and issues being addressed.

Option A Remote to Shore	Option B Direct Support	Option C Permanent SSES
• Data viewed from geographically remote center. • Intelligence collection processing from consolidated center requires less intelligence personnel on ships. • Consolidating capabilities into central center popular movement to cut costs and provide more shore based operations to support war-fighting capabilities. • Similar to consolidation of service operations in businesses into larger and fewer call centers.	• CCOP equipment & operators move from ship to ship whenever a ship came into port for maintenance, repair or modernization. • Fewer sets of CCOP equipment and operators required to service intelligence gathering needs of the fleet.	• CCOP systems and operators assigned to given ships at all times. • Requires more operators and CCOP systems. • Potential costs increases, provides more control of intelligence capability by the ships and fleet commanders.

Table 22: CCOP Strategic Scenarios

Each strategic scenario is explored further.

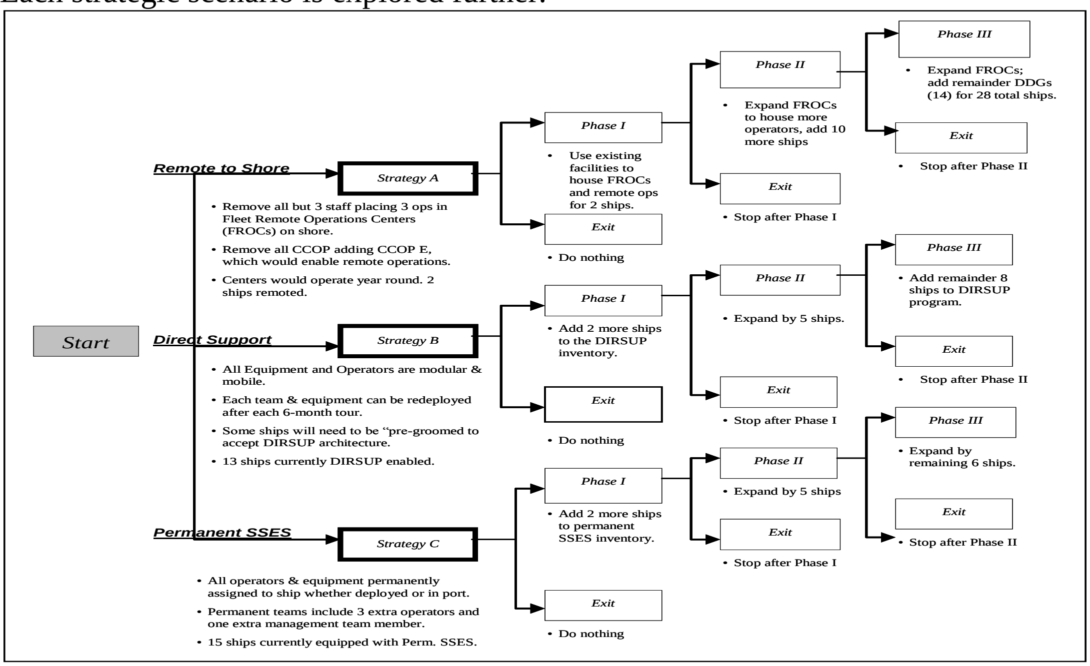


Figure 24: Real Options Analysis of Strategic Scenarios

	Option A	Option B	Option C
PV Option Cost (Year 1)	$348,533	$1,595,697	$1,613,029
PV Option Cost (Year 2)	$4,224,487	$3,043,358	$4,494,950
PV Option Cost (Year 3)	$3,688,994	$10,105,987	$8,806,643
PV Revenues	$24,416,017	$33,909,554	$38,820,096
PV Operating Costs	$16,220,188	$16,765,513	$9,951,833

PV Net Benefit	**$8,195,829**	**$17,144,041**	**$28,868,264**
PV Cost to Purchase Option	$425,000	$169,426	$72,611
Maturity Years	3.00	3.00	3.00
Average Risk-Free Rate	3.54%	3.54%	3.54%
Dividend Opportunity Cost	0.00%	0.00%	0.00%
Volatility	26.49%	29.44%	15.04%
Total Strategic Value with Options	**$1,386,355**	**$4,466,540**	**$15,231,813**

Table 23: Summary Real Options Analysis Results

Conclusions and Recommendations

Applying the KVA+RO framework to the USS READINESS demonstrates how defensible and relatively objective metrics could be derived for analysis of each CCOP's ROI performance in the portfolio.[5] Based on results of our initial research, we make several recommendations:

- ***Expand scope of initial study***. KVA methodology should be applied and analyzed over a larger sampling period to accurately measure the impact of CCOP systems. A larger study should be conducted on CCOP systems at the Carrier Strike Group (CSG) or Expeditionary Strike Group (ESG) level over the course of one deployment to begin establishing performance baselines for systems and processes.[6]

- ***Collect additional process data.*** Supplemental data on human and automated processes should be collected to attain near real-time performance data reporting. Automated logging of system utilization and performance are readily available in many business applications. Adapting such mechanisms for use with CCOP systems would facilitate the performance analysis.

- ***Implement KVA software for real-time analysis.*** Although several accounting software packages have included KVA analytical capabilities, the NPS research team has identified GaussSoft KVA software as the most comprehensive software platform for conducting the level of analysis required by DoD program managers. Implementing GaussSoft software allows real-time system and process

[5] KVA analysis was conducted on a limited set of data. To obtain a more comprehensive picture of CCOP system contribution, multiple iterations of this analysis would have to be run across the Navy-wide enterprise of intelligence collection platforms to obtain a comprehensive understanding of CCOP program contribution.

[6] Currently in process with the Third Expeditionary Strike Group.

inputs to be received, as well as proof-of-concept and a testing of the operational capabilities of the software. 7

- ***Expand research study to include other public and private sector organizations.*** An extensive research study should be conducted on the Market Comparables Approach to include a valuation study of the intelligence products produced by private military corporations, along with competitive and business intelligence organizations to achieve a baseline price per unit of output metric. One of the study's primary objectives would be to develop universally accepted descriptions of embedded knowledge and required learning time of each system and process.

- ***An external organization should be selected to maintain KVA databases for CCOP systems***. This organization would act as the central repository for system performance data to provide reports and analysis on a quarterly or semi-annual basis enabling program managers to make informed acquisition decisions. This data could be expanded to include other systems and core processes to benchmark performance across the enterprise.

B.3: Modular Munitions Case Study

Introduction

The DoD is often criticized for point design systems that are made obsolete by changes in the world situation by the time a system completes development, test and deployment. While this criticism may be well founded in some cases, there are many DoD systems that have been designed with flexibility in mind, and they have been successfully used in operations for many years, and even decades. Examples such as these can be used as case studies to formalize and test out methodologies and tools for weighing and valuing flexibility in design to support future acquisition decisions. One promising case study is associated with the air-delivered munitions employed by the United States' Air Force and Navy. Researchers at AFIT have recently looked at the GBU-24 Laser Guided Bomb (LGB) and GBU-31 Joint Direct Attack Munition (JDAM) as part of their investigations into modularity. That case study is now being expanded to support the present investigations into flexibility under RT-18.

Background

In the 1960's the DoD initiated the development of the Paveway series of guided bombs. This was initiated as a low cost initiative to allow precision delivery of existing warheads. Initially designed to work with the M117 bomb, they were later adapted for use with the newly designed Mk 80 series of bombs. The Mk-82 (500 lb), Mk-83 (1000 lb) and Mk-84 (2000 lb) bombs are the warhead component of many munitions used by both the Air Force and the Navy (see tables below). Development of the Paveway series continued in the 1970's (Paveway II) and 1980's (Paveway III) resulting in a family of munitions that can be used for a wide range of targets and delivery profiles. The 1980s saw development of a new penetrator bomb, the 2000 lb BLU-109, that could be used with the Paveway guidance kit to address sub-surface and/or hardened targets. In 1991 the Paveway III was rapidly modified to accommodate a hastily developed 4700 lb warhead, originally produced from deactivated howitzer barrels (later produced as BLU-113, and later still, BLU-122 warheads). This "bunker buster" bomb was conceived, developed, tested, deployed and operationally used within a two month period! As stated above, the Paveway family of munitions accommodated a wide range of applications; they could be assembled in the field in response to a daily Air Tasking Order using an array of options in terms of warheads, fuzes, guidance kits, and delivery aircraft. Consistent with definitions provided under RT-18, the Paveway systems appear to capture elements of both adaptability (in the field) and flexibility (easily modified) to achieve new capabilities.

PAVEWAY Munition Variants (courtesy of Wikipedia)

- GBU-10 Paveway II – Mk 84 2000 lb (907 kg) bomb

- GBU-12 Paveway II – Mk 82 500 lb (227 kg) bomb
- GBU-16 Paveway II – Mk 83 1000 lb (454 kg) bomb
- GBU-22 Paveway III – Mk 82 500 lb (227 kg) bomb. Developed at the same time as GBU-24, with some limited export success, but was not adopted by USA as it was felt to be too small of a warhead for the desired effects at the time.
- GBU-24 Paveway III – Mk 84/BLU-109 2000 lb (907 kg) class bomb
- GBU-27 Paveway III – BLU-109 2000 lb (907 kg) bomb with penetration warhead, specially designed for F-117 because the large fins of GBU-24 couldn't fit into the bomb bay of F-117.
- GBU-28 Paveway III –The latest warhead used in the GBU-28/B series is the 4700 lb BLU-122/B, a development of earlier BLU-113 on early GBU-28s.
- Paveway IV – 500 lb (227 kg) bomb

In the 1990s the DoD developed a new guidance kit using a combination of Inertial Navigation (INS) and the satellite based Global Positioning System (GPS). These Joint Direct Attack Munition (JDAM) guidance kits (see table below) were made to be compatible with existing warheads and fuzes, resulting in an expanded family of munitions available to the Air Force and the Navy. As in the Paveway series of guided bomb, they could be assembled in the field according to the daily Air Tasking Order and could be delivered by most Air Force and Navy strike aircraft. The JDAM program was considered very successful by most accounts, achieving an effective system at an affordable cost with a relatively short development time compared to other munition programs being pursued during the same period of time. The 1990s also saw the development of the Advanced Unitary Penetrator (BLU-116) warhead that could be used with existing fuze and guidance kits (JDAM and Paveway) to achieve greater penetration than that achievable with the BLU-109. Additional fuze modules were developed as well, to include the Joint Programmable Fuze (FMU-152) and the Hard Target Smart Fuze (FMU-157). In addition to fielded variants of guided munitions, numerous proof of concept demonstrations have been conducted using modular components from the Paveway and JDAM systems. For example, prototype demonstrations of "agent defeat" warheads using incendiary fills have been conducted. Concepts utilizing these new warheads would again make use of existing modular components to reduce risk and avoid unnecessarily costly development.

JDAM Variants (courtesy of Wikipedia)

- 2,000 lb (900 kg) nominal weight
    - GBU-31(V)1/B (USAF) Mk-84

    - GBU-31(V)2/B (USN/USMC) Mk-84
    - GBU-31(V)3/B (USAF) BLU-109
    - GBU-31(V)4/B (USN/USMC) BLU-109
- 1,000 lb (450 kg) nominal weight
    - GBU-32(V)1/B (USAF) Mk-83
    - GBU-32(V)2/B (USN/USMC) Mk-83
    - GBU-35(V)1/B (USN/USMC) BLU-110
- 500 lb (225 kg) nominal weight
    - GBU-38/B (USAF) Mk-82,(USN/USMC)Mk-82 and BLU-111
    - GBU-54/B LaserJDAM (MK-82)

Not all munitions in the inventory are modular in design, so it may be useful to compare the modular Paveway and JDAM series to alternative approaches. Possible examples include the Small Diameter Bomb (SDB) or the Joint Air-to-Surface Standoff Munition (JASSM). Both of these munitions are better described as integral designs. JASSM, emerging from an Acquisition Reform pilot program of the 1990s, was developed to meet threshold requirements at minimum cost. Consideration of flexibility (or adaptability) appeared to be set aside in favor of trying to control cost and keep the program on schedule. Any future consideration of additional warhead types for JASSM (such as area defeat mechanisms) would likely be met with high modification costs because of how the base warhead was accommodated in the original design. In the case of the SDB, very tight space and weight constraints to allow for internal bay carriage drove the developers to a more integral design. This is a well known tradeoff between modular and integral designs, and can be seen in consumer products as well. Examples include larger desktop personal computers (more modular in design to accommodate product variety) vs. notebook computers designed for space and weight constraints, yielding more integral designs that are not as easily expanded or modified.

Candidate Case Study Structure

One of the questions being addressed by RT-18 is that of how to design a system (or justify the candidate design) so that its capabilities can be easily (in terms of time and money) increased in response to new requirements or previously unanticipated operational scenarios. In order to do this, one needs to be able to quantify capability, or changes in capability, the perceived value of obtaining the new capability, and the cost of achieving the new capability. The latter of these, the realm of cost estimation, can be

done using analogous, parametric and engineering cost approaches for a given system based on the availability of data. Models such as COSYSMO and COPLIMO, developed by Boehm, Laine, et.al., represent refinements of the parametric approach and are being examined to accommodate new parameters associated with flexibility. Examples of parameters that may have an impact on flexibility include, but certainly are not limited to, modularity and its sub-measures of reconfigurability and extensibility. Recent work [Stryker, Jacques, 2010] has demonstrated methods for quantifying these modularity measures based on the functional and physical architecture of the system, and extensions of these methods to higher level concepts are possible.

The value associated with a change in capability must be related to what the user or sponsor would be willing to pay, or give up, in order to achieve it. This obviously relies on quantification, or at least clarification, of the changes in capability associated with the development under consideration. In order to provide quantification of capability, a basis for comparison must be constructed that identifies the different tasks that can be accomplished as well as the degree to which they can be accomplished. The DoD's Universal Joint Task List (UJTL), [CJCSM3500.04C], provides an authoritative list of military tasks as well as suggested conditions and measures appropriate for the individual tasks. Hierarchically organized at Strategic National, Theater, Operational, and Tactical levels, the UJTL attempts to provide an exhaustive glossary for all tasks that the military may need to perform in order to deploy, operate and sustain forces in support of national defense. However, the very scope of the UJTL results in tasks defined at a generally high level of abstraction. For example, if we look for tasks associated with the delivery of munitions, we come up with the following tasks from the UJTL:

Candidate Tasks From the Universal Joint Task List

OP 3.2 Attack Operational Targets
OP 3.2.1 Provide Close Air Support Integration for Surface Forces
OP 3.2.2 Conduct Non-Lethal Attack
OP 3.2.4 Suppress Enemy Air Defenses
OP 3.2.5 Interdict Operational Forces/Targets
OP 3.2.5.2 Conduct Surface/Subsurface Firepower Interdiction of Operational Forces/Targets
OP 3.2.6 Provide Firepower in Support of Operational Maneuver

Note that these tasks are very general and do not immediately support quantifying varying levels of capability between different munition systems. A possible extension of the UJTL approach can provide a more useful delineation of capability as follows:

Extended Definitions for Strike Related Tasks

OP 3.X.X Defeat fixed surface targets
OP 3.X.X Defeat mobile surface targets
OP 3.X.X Defeat sub-surface targets
OP 3.X.X Defeat Area Targets
OP 3.X.X Defeat Chem/Bio Facilities
OP 3.X.X Limit Collateral Damage (possibly an attribute/measure of other tasks)
OP 3.X.X Survive enemy air defenses

Extensions such as these could be used to distinguish capability resulting from varying warhead and/or guidance options associated with a munition development program (similar extensions can be developed for other mission areas). Conditions, attributes and measures associated with these extended task definitions also need to be defined in order to quantitatively compare system approaches. Normalized measures can be used to define a "weighted capability volume" based on how much of the capability is achievable for a given system concept. This capability measure should also provide the basis for the value of the capability, although additional approaches will be required to solicit value assessments from users or sponsors of the systems under consideration. The Value Driven Design approach of Collopy and others will likely be important in establishing the value associated with a given concept.

Once a basis for comparison of achievable capability is established, the design features of a system that enable it to achieve those capabilities must be identified. The design features and other parameters associated with, for example, modularity and interoperability, will be necessary to support cost estimates. For the case of munitions, recently completed work can be extended to support flexibility assessment under RT-18. [Stryker and Jacques, 2010] and [Oyama, Stryker, Jacques and Long, 2010] used the munition case study to support investigations into modularity and its possible relation to rapid assembly and check-out processes. That work used functional, physical and interface definitions of the system to establish modularity measures associated with reconfigurability and extensibility (and others). These measures provided indications of the adaptability and ease with which the system might be modified to achieve new capabilities, contributing to the overall flexibility of the system. While there are certainly other factors affecting flexibility that need to be uncovered, this recent work provides a useful starting point for this investigation under RT-18.

Case Study – Way Forward

Ongoing and planned extensions to the existing munition case study are as follows:

- Using suitable definitions of tasks, attributes and measures, characterize the capability space associated with the broad mission area driving the need for strike munitions.

- Identify an additional munition program to be investigated for this case study. The Paveway LGB and the JDAM have initial work done on them in terms of functional, physical and interface definitions, but it would be useful to have a third munition program representing a more integral design to compare with the modular designs of Paveway and JDAM. SDB and JASSM were mentioned above as candidate systems for comparison, but AFIT is currently assessing the availability of data to support the case study for those and other systems.

- Gather the programmatic data to support the case study. Specific data needs are being driven by the downstream methods associated with estimating programmatic flexibility, to include the COSYSMO/COPLIMO, Hedge Frameworks, or Real Options valuation models. Anticipated data needs include:

    - Program/acquisition structure, to include planned, and not-previously planned options that were considered and/or exercised;

    - Requirements evolution, to include requirements not accommodated by design/development;

    - Cost evolution for base programs and options/mods pursued (actual cost would be preferable for the case study, but we need to consider consistent sourcing of the data across all programs considered);

    - Cost estimates for options not (yet) exercised.

- Quantify the measures of capability associated with the various munitions.

- Gather inputs from users to provide an assessment of value for the munition systems and other options that may still be available for future munition development.

- Evaluate the programmatic flexibility achieved at various stages of the life cycle for the munitions.

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